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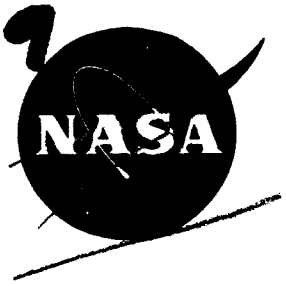

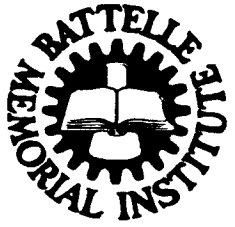

ACE IWI

Automatic Checkout Equipment and Techniques

Seminar

Symposium

PROCEEDINGS

(NASA-TM-101109) PROCEEDINGS OF THE 2ND SEMINAR ON AUTOMATIC CHECKOUT EQUIPMENT AND TECHNIQUES (NASA) 401 p

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Battelle Memorial Institute

November 13 and 14, 1963

Preface

The co-sponsorship of the Seminar is not to be construed to mean endorsement by the sponsors of the information disseminated at the Seminar. Sponsorship was granted to promote the exchange of technical information, and the contents of these Proceedings do not necessarily represent policies, recommendations, or conclusions of the National Aeronautics and Space Administration or of Battelle Memorial Institute.

This is the second seminar on automatic checkout co-sponsored by Battelle; the first was held on September 5 - 7, 1962. Proceedings were published for both seminars. Additional copies may be obtained from the Institute as long as the supply lasts. The charge for the Proceedings for the first (1962) Seminar is $5.00 and for the second (1963) Seminar is $5.25. Inquiries should be directed to:

Battelle Memorial Institute
Room 10-124
505 King Avenue
Columbus, Ohio 43201

PROCEEDINGS

SECOND SEMINAR

on

AUTOMATIC CHECKOUT EQUIPMENT AND TECHNIQUES

held at

Battelle Memorial Institute
Columbus, Ohio

November 13 and 14, 1963

Sponsored by

The NASA-George C. Marshall Space Flight Center
and Battelle Memorial Institute

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Washington 25, D. C.

CARL W. STEEG, JR., I.T.T. Industrial Laboratories (Ft. Wayne).

Dr. Steeg received an AB degree (DePauw University, Michigan State), BSEE degree (Oregon State) and PhD degree (M.I.T.). He has been active in the fields of systems analysis, evaluation, analog and digital computation and flight simulation of guided weapons; synthesis of nuclear-reactor controls, autopilots, and stability and control augmentation devices for guided and ballistic weapons; statistical optimization theory in nonlinear, adaptive, and sampled-data control systems; automatic checkout and malfunction detection techniques; human factors; sensors, instruments, and data processors. He has held many supervisory positions. He is a Fellow of the American Association for the Advancement of Science, and is a member of the American Mathematics Society, American Ordnance Association, Sigma Xi, and the Society of Industrial and Applied Mathematics. Present position: Director, New Product Planning and Development.

IN-FLIGHT MANAGEMENT SYSTEM TECHNIQUES FOR BOOST VEHICLES

Carl W. Steeg, Jr.

SECOND SEMINAR

on

AUTOMATIC CHECKOUT EQUIPMENT AND TECHNIQUES

Introduction

The first seminar on automatic checkout techniques was organized to bring together people who are working on and directing research in the area of automatic checkout techniques (ACT). The enthusiastic response to this seminar prompted Battelle to organize a second seminar and, when the National Aeronautics and Space Administration - The George C. Marshall Space Flight Center graciously accepted the invitation to be a co-sponsor, the program was expanded to include a discussion of equipment (ACE). The call for papers received a larger response than could be accommodated and it was with regret that many excellent papers were declined.

The written versions of the papers are presented in these Proceedings exactly as submitted by the authors. The presentation on Project FIST (Fault Isolation by Semi-Automatic Techniques) is reported in summary form by request of the authors. It is understood that complete papers on this project will be published in scientific journals next year. The tutorial session on PLACE also is abstracted. A Battelle report on this will be issued within the year.

The sponsors are extremely grateful to the authors for their presentations and papers; to Dr. Thomas for his welcoming address; and to Mr. Vogt and Col. Fellows for their luncheon talks. The success of the seminar reflects the long hours of work by the committees and in particular the work of Mr. Phil Youngblood, the NASA coordinator, and Mr. Kenneth Hobbs, Mr. George Rogers, Mr. Mike Tikson, and Mr. Robert Yereance, who served on various committees.

Dr. K. L. Nielsen
Chairman of the Seminar

Program

November 13, 1963 - Morning

8:00 - 9:15 Registration - BMI Auditorium

9:30 - 9:45 Welcome Address - B. D. Thomas, President
Battelle Memorial Institute

TECHNIQUES AND THEORY - Chairman, Kaj L. Nielsen
Battelle Memorial Institute

9:45 - 10:30 In-Flight Management System Techniques for Boost Vehicles - Carl W. Steeg, Jr., I. T. T. Industrial Laboratories

10:30 - 11:10 Precise Estimates of Systems Dynamics From Normal Operation Records - Arthur Mace, Battelle Memorial Institute

11:10 - 11:50 Integrated Vehicle Checkout System Error Analysis
R. J. Allen, Autonetics Division of North American Aviation, Inc.

12:15 - 1:45 Luncheon - Automatic Checkout – Will it Pay Off?
Mr. Stuart H. Vogt, NASA Headquarters, Washington

November 13, 1963 - Afternoon - TUTORIAL SESSIONS

I. Automatic Checkout - Main Auditorium
Chairman, Robert Yereance, Battelle Memorial Institute

2:00 - 3:30 The Systems Engineering Approach to Automatic Checkout – 3 integrated papers by
J. J. Coleman, R. A. Kirkman, and M. C. Peterson
Space Technology Laboratories, Inc.

3:45 - 4:45 Project FIST – Fault Isolation Semi-Automatic Technique – 2 integrated papers by
Gustave Shapiro and Owen B. Laug
National Bureau of Standards

II. PLACE – Programming Language for Automatic Checkout Equipment
(Limited to attendees experienced with programming computers or checkout equipment)
Chairman, Michael Tikson, Battelle Memorial Institute

2:00 - 3:30 Part I – Burton H. Went, Battelle Memorial Institute
3:35 - 4:45 Part II – William R. Irion, Battelle Memorial Institute
5:30 - 6:30 Hospitality Hour

November 14, 1963 - Morning

APPLICATION – Presentation by NASA-MSFC
Chairman, H. J. Fichtner, Chief
Electrical System Integration Division

9:00 - 10:30 LAUNCH SITE CHECKOUT – Astrionics Laboratory

1. The Role of Electrical Systems in the Saturn Cape Operations
   R. M. Aden, Chief, Sys. Oper. Design Branch
   E. T. Baggs, Deputy Chief, Sys. Oper. Design Branch
   G. P. Barr, Technical Assistant (Auto. Check.)
2. Operational Computer System
   F. S. Wojtalik, Technical Assistant
   (GSE, G&C Division)

10:35 - 11:50 FACTORY CHECKOUT – Quality Assurance and Reliability

1. Practicalities in Automated Manufacturing Checkout
   Robert L. Smith, Jr., Res. Proj. Coord.
2. Future Tests and Checkout Concepts
   R. W. Foster, Chief (Adv. Check. Unit)

12:00 - 2:00 Luncheon – The RIFT Program
Col. W. Scott Fellows, NASA-MSFC

November 14, 1963 - Afternoon

COMPUTERS AND EQUIPMENT – Chairman, Richard Forbes, IBM Corporation

2:00 - 2:40 Computer Controlled Testing with DEE
Bradford T. Joyce, Aerospace Systems Division, RCA

2:40 - 3:20 In-Flight Checkout System Using Computer Control
Frank Medved, Aeronautical Division, Honeywell, Minneapolis

3:20 - 4:00	VATE – Design and Operational Characteristics Victor Mayper, Jr., Hughes Aircraft Company
4:00 - 4:45	Man-Machine in Automated Test Operations – Saturn S4B George Meister, Douglas Aircraft Company

Additional Papers

An Application of Artificial Intelligence To System Testing –
John C. O'Brien, Nortronics.

A New Digital-To-Voice Conversion Device –
D. S. Durie and E. F. Clune, Bell Aerosystems Company

Table of Contents

Page

INTRODUCTION

PROGRAM

In-Flight Management System Techniques for Boost Vehicles – Carl W. Steeg, Jr. I-1

Precise Estimates of System Dynamics from Normal Operating Records – Arthur E. Mace II-1

Integrated Vehicle Checkout System Error Analysis – R. J. Allen III-1

The System Approach to Automatic Checkout. Part I. – Robert A. Kirkman IV-1

The Systems Approach to Automatic Checkout. Part II. – John J. Coleman. V-1

The System Approach to Automatic Checkout. Part III. – M. C. Peterson VI-1

Project FIST: Fault Isolation by Semi-Automatic Techniques – Gustave Shapiro and Owen B. Laug VII-1

PLACE – Programming Language for Automatic Checkout Equipment – B. H. Went and W. R. Irion VIII-1

The Role of Electrical Systems in the Saturn Cape Operations – R. M. Aden, E. T. Baggs, and G. P. Barr. IX-1

Operational Computer System – Fred S. Wojtalik X-1

Practicalities in Automated Manufacturing Checkout – Robert L. Smith, Jr. XI-1

Future Test and Checkout Concepts for Space Booster Systems – Richard W. Foster XII-1

Computer-Controlled Automatic Testing – B. T. Joyce and E. M. Stockton XIII-1

TABLE OF CONTENTS
(Continued)

	Page
A Computer-Controlled Integrated Checkout System – Frank Medved	XIV-1
VATE – Design and Operational Characteristics – Victor Mayper, Jr.	XV-1
Man, Machine, and Automatic Test Operations – G. F. Meister, Jr.	XVI-1
An Application of Artificial Intelligence to System Testing – John C. O'Brien	XVII-1
A New Digital-To-Voice Conversion Device – Douglas S. Durie and Elmer F. Clune	XVIII-1
About the Authors and Committee Men	

Technical Papers

IN-FLIGHT MANAGEMENT SYSTEM TECHNIQUES FOR BOOST VEHICLES*

ABSTRACT

The critical schedule of the national program for space exploration demands the maximum contribution from every launching. This requirement dictates that each major system, subsystem, and component be designed and produced to meet the most stringent performance and reliability standards in order to assure mission success.

With the development of large multi-stage launch vehicles, and with contemplated payloads destined for such intricate operations as rendezvous and lunar landings, it is no longer adequate that check-out should terminate with the countdown - but it must proceed during count-up, that is, during operational flight. Although these vehicles are being designed with a high degree of simplicity and consequent inherent reliability and although automatic ground check-out equipments maximize the operational readiness status prior to launch, nevertheless the sheer magnitude of the total equipment complex is such that unexpected malfunctions after launch cannot be discounted. For this reason, a supplemental scheme for maintaining the probability of mission success during flight at the same high level predicted by the automatic grand check-out equipment prior to launch has been studied thoroughly. This scheme, originally conceived under the designation Operational Flight Control, is now more widely known as an In-Flight Management System (IMS). Following a brief mention of the overall IMS characteristics and a somewhat lengthier description of the data-processing require

* Carl W. Steeg, Jr., I.T.T. Industrial Laboratories

ments for in-flight management, certain hardware techniques based on imaging equipment and useful for predicting the onset of malfunction and for triggering remedial action will be discussed.

In-Flight Management System Description

Predominantly this seminar is concerned with ground-based automatic check-out equipments which have as their prime objective the determination of the full operational readiness status of the vehicle at the completion of the checkout, some little time prior to launch. The goals in the design of such equipment and in the selection of tests to be performed are (1) that no mission-failure-causing defects go undetected and (2) that no mission-failure-causing defect is said to exist when, in fact, it does not. The impact of automatic check-out equipment on system design is profound, affecting not only the availability of test points but even maintainability in the event that repair subsequent to defect isolation is needed.

In contrast, IMS is a real-time control system for monitoring and assessing boost vehicle performance and capability during powered flight, and for adjusting in-flight parameters to compensate for subsystem malfunction or for mission deviations caused by environmental conditions or other unforeseen circumstances. Such actions complement those identified with so-called "path-adaptive guidance" programs that may inherently compensate for such malfunctions as single engine flame-out.

From ignition to payload separation, IMS continuously measures pertinent vehicle and subsystem performance values and compares these values with those required for mission success at a function of elapsed flight time. No IMS action is initiated so long as the vehicle retains the capability of achieving primary mission objectives. IMS evaluates this capability and, if a malfunction adversely affecting the primary mission is detected, institutes appropriate action to compensate for the malfunction. Should performance degradation be so serious as to threaten achievement of the primary mission, then IMS selects and initiates one of a number of pre-programmed alternate missions representing optimum utilization of the remaining vehicle capability in relation to payload requirements.

IMS performs these functions through onboard sensing and computing equipment in radio communication with a ground data processing and control center integrated with existing network and range facilities. Both the onboard IMS and the ground IMS have parallel overlapping functions to enhance system reliability. When time permits, all decisions regarding execution of corrective action are made by personnel at the IMS ground center and transmitted to the vehicle via a command data-link. In cases where there is not sufficient time for a human decision, action is automatically initiated by the onboard IMS.

Predictive techniques enable end conditions to be extrapolated, thereby providing IMS personnel with time in which to exercise best judgment in the event of pending failure.

As an example of IMS effectiveness, under the presently forecast Saturn reliability conditions, use of IMS would reduce by approximately two-thirds the number of spare vehicles necessary to accomplish a series of missions-thereby effecting significant time and cost savings to the overall space effort.

IMS Data-Processing Characteristics

The basic flight control process for Saturn launch vehicles includes the vehicle itself, a guidance system for generating instantaneous flight references, information sensors for measuring the error between the flight references and the actual vehicle altitude and related parameters by means of thrust deflection to minimize the error signals. The guidance systems also determines the time of cutoff of the engines and initiates the cutoff procedure. (Figure 1)

Because some confusion between guidance functions and IMS functions is apt to arise, some additional words of explanation may be advisable. The guidance of the S-I stage uses pre-programmed altitude commands, which are functions only of the time from lift-off. The guidance of the S-IV stage is based on the "adaptive guidance mode" and operates by accepting instantaneous vehicle data and propulsion parameters as initial conditions and by defining the optimum future flight path to meet the mission requirements. The path normally is optimized on a minimum energy

basis. In either the S-I or S-IV case, the vehicle trajectory is determined solely by onboard equipment with no provisions for alternative or remedial action (except for Range Safety Commands) in the event of failure in either the guidance on control system.

IMS extends the principle of mission flexibility by complementing the adaptive guidance concept thus enabling the vehicle to complete the primary or an alternate mission despite serious deviations due to environmental conditions or to subsystem malfunctions.

The basic in-flight management operations - some of which will be reviewed shortly in an animated film - must be carried out (1) without degrading vehicle performance and intrinsic reliability, (2) without major significant vehicle subsystem modifications, and (3) with utilization of existing range facilities and equipment. In order to meet these requirements, initial emphasis was directed toward the following data-processing characteristics of in-flight management:

(1) Measurement: Continuous monitoring of pertinent vehicle and subsystem performance values during all phases of powered flight using on-board sensors and transducers to determine current subsystem parameters and ground instrumentation for added trajectory data.

(2) Data Storage: Comparison of measured performance values with those required for mission success as a function of elapsed flight time utilizing nondestructive digital memory to effect comparison of current parameters with expected values.

(3) Computation: Analysis of deviations to determine hazards to primary mission and to localize faults.

(4) Decision and Command: Selection of one of a number of pre-planned alternate courses of action or flight plan to minimize the effect of malfunction, using stored analysis of potential situations as well as human assessment of unforeseen circumstances.

These four classes of activity are shown in Figure 2, superimposed on the basic flight control process of Figure 1. Here, the measured performance quantities from the sensors go to a computation group where, first, deviations are computed by comparison with vehicle and subsystem performance standards. These standards together with primary and alternate mode data are stored in the data source blocks of the diagram. Performance deviations are analyzed relative to the primary mission requirements, and predictions of expected mission deviations go to the decision operation, where remedial action is selected. Commands either to change the mission or otherwise to minimize the effects of failure are then inserted into the existing control system.

On the basis of the four data-processing activities, the IMS was configured as a system comprising both on-board and ground-based equipment, as shown in Figure 3. Once more, the equipment is shown in relation to the basic flight control process.

Because the scope of the IMS is so vast, a concise description of its operation is virtually impossible without the use of animated visual aids.

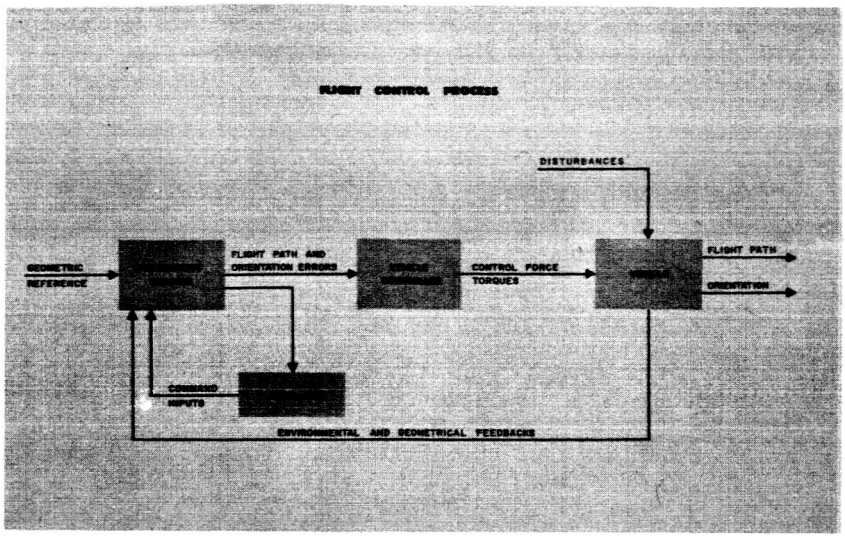


Figure 1.

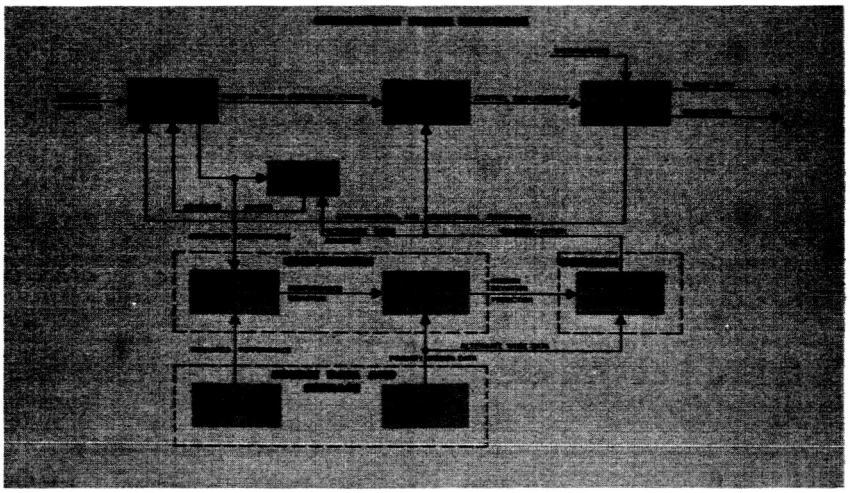


Figure 2.

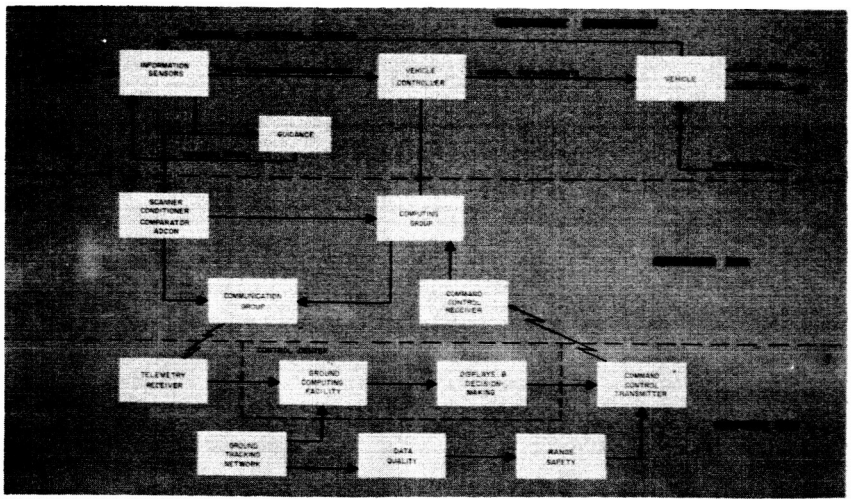


Figure 3.

Consequently, I would like to show you a short movie clip* containing some examples of potential applications of the system approach just described. Throughout the film, you will note that the system is referred to as "Operational Flight Control", a description originally introduced by NASA/Air Force personnel. It is believed that the term In-flight Management is more inclusive and will supersede the earlier designation, OFC.

Image Processing Techniques for In-Flight System Management

As you have seen in the film, the principal concern in early concept of in-flight management was with the data-processing aspects of the total problem. However, subsequent study has shown that, in general, both computer programs and equipment could be obtained within the state of the art and that the key problems were in the areas of sensing and of data-rate (bandwidth). It is concerning techniques applicable to these two problems that I would now like to turn attention, and more specifically to techniques involving imaging devices. Among the various uses of imaging devices in automatic IMS operations, three applications are probably most instructive:

(1) Image Techniques for flow and level monitoring;

(2) Image Techniques for back-up guidance; and

(3) Image Techniques for monitoring and control of combustion processes.

---

* The sound film segments are made available through the courtesy of I. K. Kessler, Vice President and General Manager, Aerospace Systems Division, Radio Corporation of America.

In recent work at ITT, it has been convenient to introduce a concept, which you may also find valuable, namely, replacing the word "data" with the word "image" in each of the following phases:

Image acquisition

Image Processing

Image translation (conversion)

Image transmission and reception

Image storage and retrieval

Image display

Image recording

Image feedback and error generation

Each of the three applications represents a different aspect of these functions.

FLOW AND LEVEL MONITORING

In the latter example of the movie, a comparison of flow-rate with level change in either fuel or oxidizer tankage permitted assessment of tank leakage. Although several electro-mechanical instruments are useful for the job of measuring cryogenic liquid or gas flow and density, all tend to alter the flow conditions by impinging into the stream itself. One electro-optical system that does not change flow conditions involves a light-absorbing gas that is fed streamwise into the center of the gas stream. This secondary gas flow attenuates downstream parallel light beams that are directed across the flow channel through windows to shine on a row of phototransistors. When both primary and secondary gas flows are steady, but have differing velocities, the difference in light absorp-

tion at successive stations provides data adequate for calculation of the primary gas density. When secondary gas is introduced as a bubble, the time interval between interference at downstream monitoring stations indicates flow-rate. Despite nominal cost, however, the system may be accused of violating the non-interference requirement of contributing to unreliability because a valve or Pitot for introducing the secondary gas and windows for observing flow are needed; thus seams, welds, and bonds are required.

A second opto-electronic system for flow measurement uses a radioactive trace element mixed with the primary cryogenic liquid. As the liquid flows through the vehicle plumbing, a multiplier phototube (Type FW118) detects passage of the radioactive material. A unique design feature facilitates unambiguious detection of single photoelectron events by producing Poisson-type pulse-height statistics in contrast to the more usual exponential-type. This image intensifier phosphor conversion process may be used with a scintillator or Cerenkov radiator or, in particular, as a tritium soft-ray detector. This measurement permits determination of density and, in a second or scanning mode, of the fluid flow rate. (Figure 4)

Another approach, similar to windowless gas flow counters, involves a combination of image intensifiers and spark chambers in which single photoelectron from a photocathode triggers a gas discharge in a two-dimensional array of microscopic tubes, each tube essentially a miniature fluorescent light, with gas isolation by means of a Lenard window.

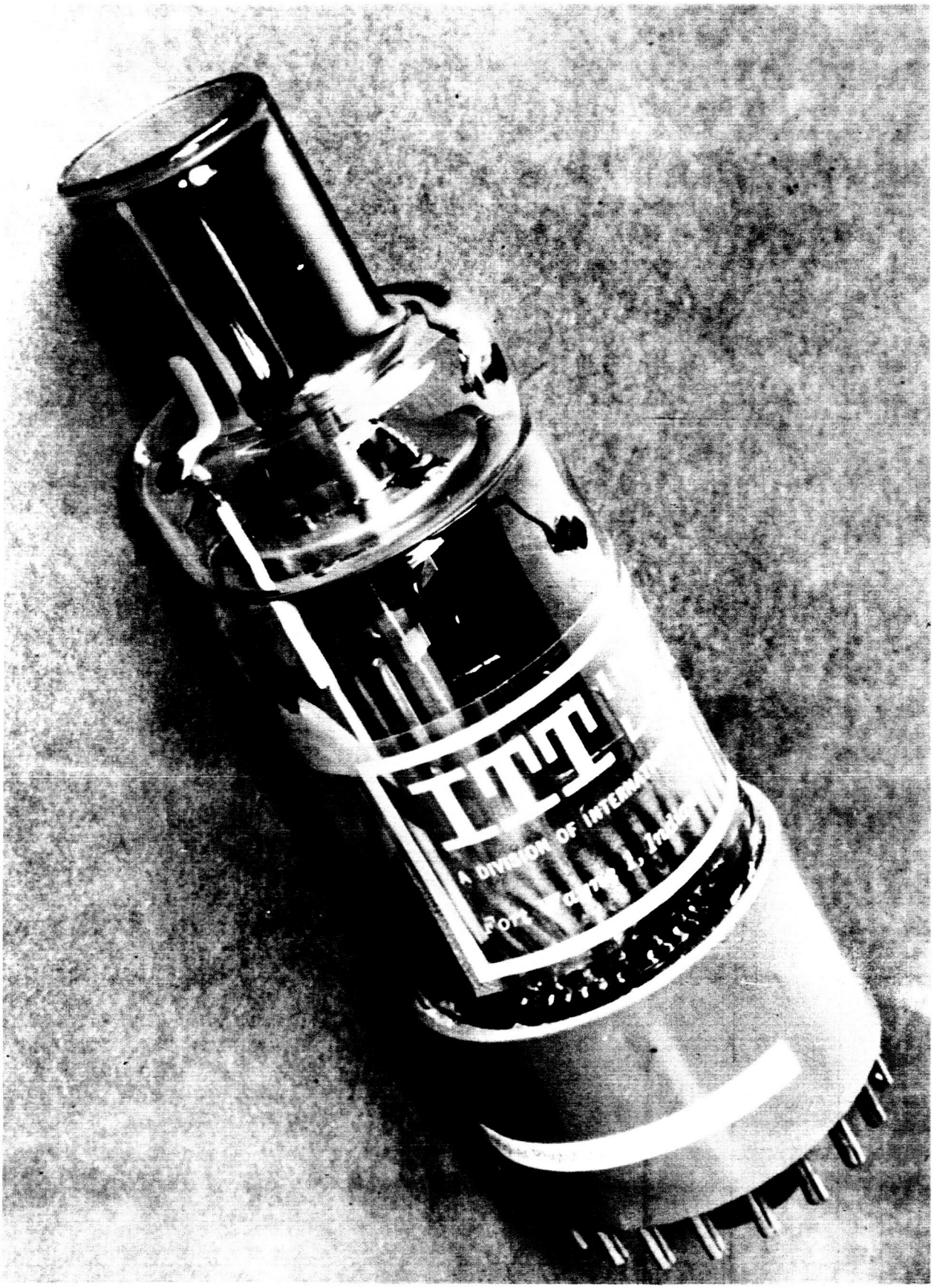


Figure 4.

Radioactive techniques which must be considered untried because of their limited development have been largely confined to laboratory testing with little thought to in-flight leak monitoring. Unfortunately, from my present viewpoint, semi-conductors, because they are compact and resist vibration and shock, appear most feasible for testing boost vehicles in flight. (Figure 5)

Because this equipment is still experimental, there is little further information available. However, it should be pointed out that a photo-tube technique is currently used for level sensing in Saturn S-1 tankage.

BACK-UP GUIDANCE

The whole subject of guidance, as I have mentioned before, merits more detailed discussion than we can give here - largely because of the versatility and ingenuity of the guidance concept. In theory, the guidance equations are inherently capable of providing corrective commands to compensate for the majority of most probable malfunctions, except those in the guidance system itself. In practice, the full capability of the theory is not realized - either because of the a'priori computations involved in determing the most general set of guidance coefficients is prohibitive or because of limitations in the input - output and storage capacity of the ASC-15 computer which, although representing the most proven spaceborne computer, was not specifically tailored to Saturn requirements.

Nevertheless, back-up equipments should be provided in order that, if guidance failure occurs, the payload may achieve some orbit, or at least, be recovered in a controlled manner. Even though, back-up can be achieved

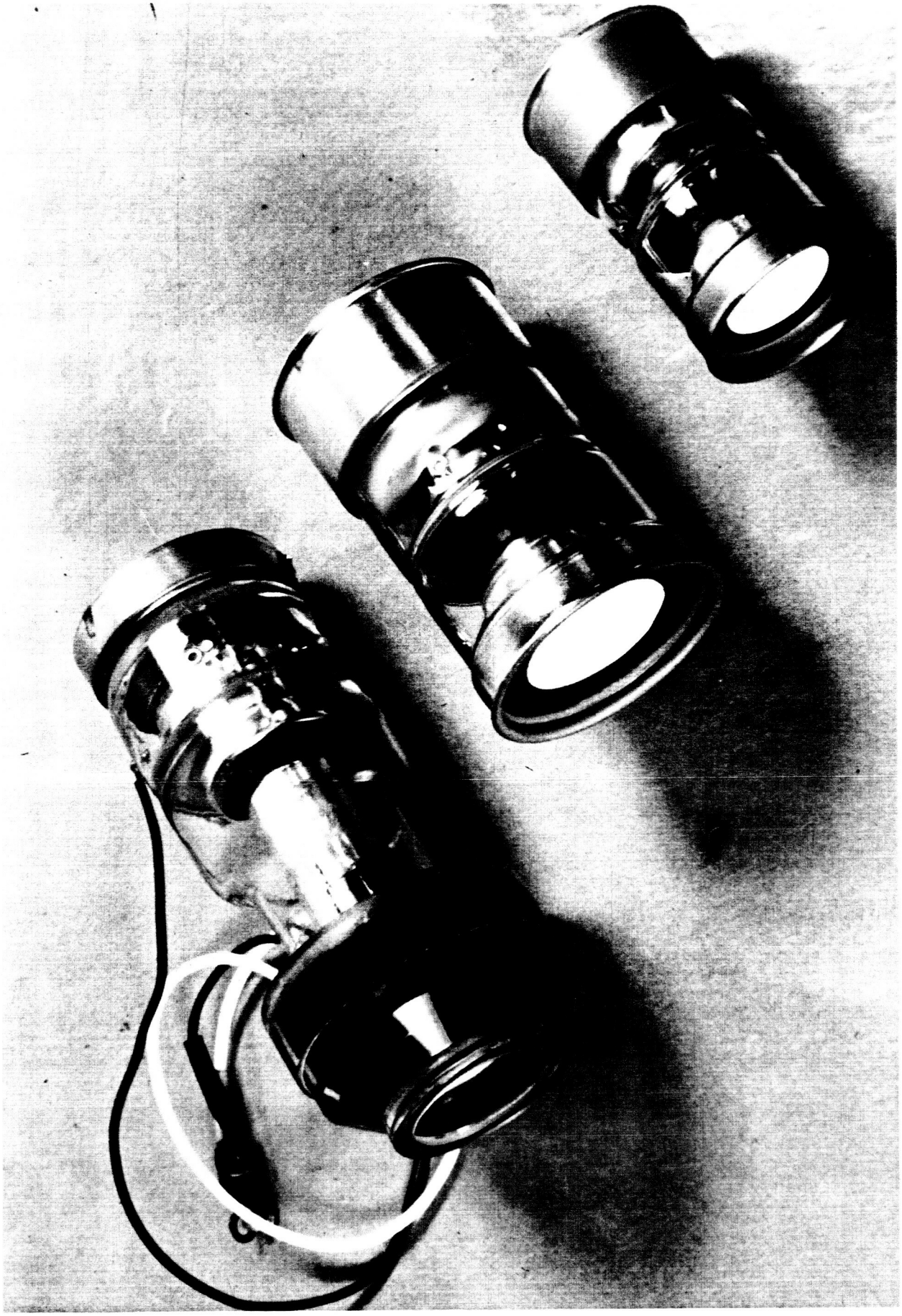


Figure 5.

through replication of hardware, a more practical approach is to duplicate the function, but by utilizing a different physical phenomenon as a basis. Because current guidance is inertial (or radio-inertial), one appropriate back-up is through electro-optical means.

Most present-day electro-optical guidance devices belong to either of two categories: (1) those that employ optical image splitting and consequent balance of direct-current outputs from multiple photocells, or (2) those that employ mechanical motion (eg. rotation or mutation of a reticle) somewhere in the optical path and recover the guidance signal from the ensuing modulation.

An example of the former type is the Digital Doppler Velocity meter designed originally by Kearfott Company, Inc. The system measures vehicle velocity relative to a prominent star by computing Doppler shift. Stellar light energy is collected by the external mirror and directed onto a convex mirror, from which is reflected into a fiber-optic light funnel. The Cassegrainian-type telescope thus formed constitutes an off-axis focusing arrangement which permits more compact internal instrumentation. The slit at the output of the light funnel forms the input to the spectroscopic systems comprising: (1) a collimating lens, (2) a diffraction grating through which light is reflected and analyzed into its various wavelengths; the H_γ component is reflected in the direction of (3) the cylindrical concave mirror which, together with two other mirrors, forms a 24" optical path to focus the H line.

The dividing mirror (prism) divides the spectrum near 4340 A^o (H_γ) into two parts and reflects each part into a secondary prism, which in turn

reflects these parts into a photomultiplier. Because hydrogen nuclei in the star absorb energy at 4340A°, the spectral intensity shows a minimum at this value. One phototube normally receives light power from 4335A° to 4340A°, and the other from 4340° to 4345°, thus tending to balance. Wavelengths outside this band are not transmitted by the prisms. If a Doppler shift occurs, one phototube receives more light-power than the other, causing an imbalance. The outputs of the photo-multipliers are coupled to a bridge network with an output that is the difference of the respective photoluminosities. When a Doppler shift occurs, the bridge output represents an error signal that, when amplified and applied to the capture coil, induces a magnetic force between the coil and the capture magnet. This force causes the assembly consisting of the coil, the prisms, and a variable capacitive plate to displace linearly until the error signal is nulled. The amount of displacement is proportional to the H_γ Doppler shift. The variable capacitive plate provides a second bridge network for measuring this displacement by digital metering of the beat frequency of two local oscillators. Although displacements are minute, velocity resolutions corresponding to 60 mi/hr are achievable. With the known motion of the star relative to the sun, it is, therefore, possible to control thrust cutoff sufficiently well to achieve orbit if the vehicle altitude is appropriate.

Vehicle altitude can be assessed by a star-tracker assembly which the pitfalls of either image-splitting or mechanical scan. The first type suffers from well known problems of stability in high-gain direct-coupled

circuitry and is often excessively bulky due to the multiplicity of phototubes. The second type usually has the disadvantage of a high noise level introduced by mechanical vibration and is sometimes limited in response by practical mechanical reticle speeds. A special multiplier phototube (FW-129) that has a deflectable image tube section at its front end avoids these problems. By magnetic deflection of the electron image, motion of the image can be obtained without mechanical nutation of a reticle. This scheme is shown in Figure 6, together with the scanning pattern.

For explanation, let us assume a dark field of view with a star at the geometric center. The light is focussed onto the photocathode and again imaged, electronically through an aperture to the first dynode of the multiplier. As the electron image is deflected progressively to the right, it passes beyond the edge of the aperture, thus terminating the electrical output from the multiplier. In a similar manner the image is deflected sequentially up, left, down, right again, and so on. The resultant output pulses are gated alternately into two channels, one for left-right control and the other for up-down control. The pulses in either channel have such symmetry that they contain no energy at the fundamental scanning frequency, but do have a strong component at double this frequency.

When the undeflected star image is off center, say, to the right as shown, the resulting pulse train lacks symmetry, having a longer off time to the right than to the left. This asymmetry causes a fundamental component, the phase of which is indicative of the direction in which the image is off center and which is proportional in amplitude to the amount of offset displacement. Thus, the output is available in a form suitable for application to the control winding of a two-phase servo

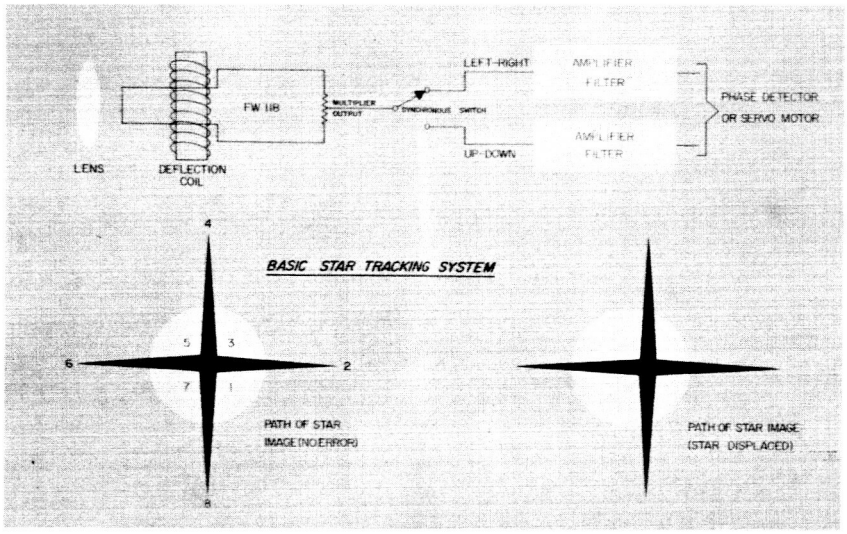

LENS
DEFLECTION COIL
FW 118
MULTIPLIER OUTPUT
SYNCHRONOUS SWITCH
LEFT-RIGHT
UP-DOWN
AMPLIFIER
FILTER
AMPLIFIER
FILTER
PHASE DETECTOR OR SERVO MOTOR
BASIC STAR TRACKING SYSTEM
4
5
3
6
2
7
1
8
PATH OF STAR IMAGE (NO ERROR)
PATH OF STAR IMAGE (STAR DISPLACED)

Figure 6.

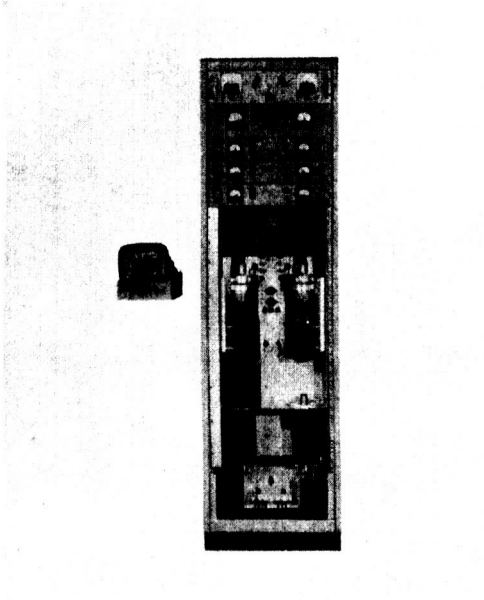
motor or to a phase-sensitive rectifier.

COMBUSTION PROCESS AND PLUME MONITORING

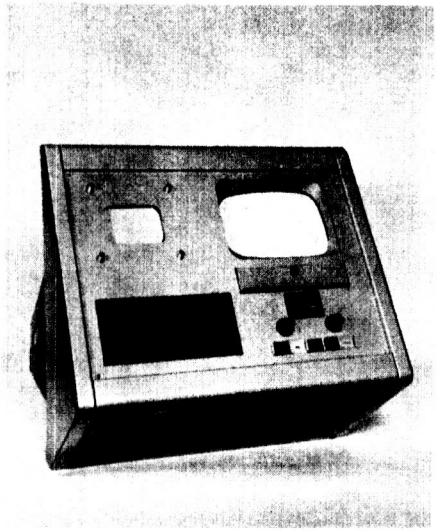
A significant example, shown in the film, relates to engine shutdown if the combustion is improper. Correlation of measurements from several vibration, temperature, pressure, and both fuel and oxidizer flows transducers is required; and even all these measurements may not permit sufficient lead time in detecting combustion instability because so little is known about how these large engines really work. Probably the best way to monitor engine performance is visually.

At present, Saturn engines are monitored in flight by four television cameras so mounted on the trailing edge as to permit a view of the shock diamonds and the plume dimensions. The pictures are transmitted over a wide-band data link on a time shared basis to a ground facility having four separate television monitors. An ITT developed controlled storage television set, which is a combination of a storage-tube display, a vidicon camera, and a standard CRT monitor is used to convert the non-repetitive television images into a flicker-free constant-brightness display. The system depends on the inherent characteristics of a direct-view storage tube called the Iatron, which also allows manual selection of a particular frame to be held and viewed for extended periods in order that the combustion process at a critical time may be analyzed. Both the viewing unit and the study unit are shown in Figure 7. By combinations of operating modes, it is possible to store, process, evaluate, transmit, and display television images for application to many IMS functions. For example, the system might find important application as an astronaut display.

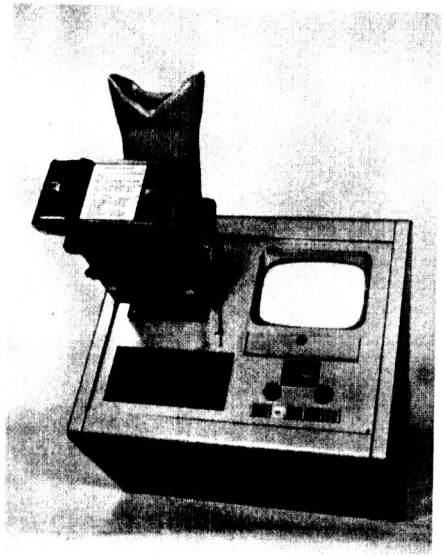
CONTROLLED STORAGE TV



VIEWING UNIT



STUDY UNIT



STUDY UNIT WITH
POLAROID CAMERA

Figure 7.

The concept also can be extended to include such IMS-oriented use as for image feedback, error generation, and control actuation, as follows. Instead of an Iatron, a Barrier Grid Storage Cathode Ray Tube is used (Fig. 8). This tube has the important property that, if a pattern of repetitive signals is applied to the metallic target substrate in synchronism with the scanning electron beam, no signal appears at the output of the tube. If a moving target is present in the pattern of repetitive signals, only the moving target appears on the output. When the plume is viewed in this mode, only fluctuations in shock diamond configuration and growth of the plume fringes (due to the change in atmospheric density) are observed. The total luminosity can be integrated over the tube face by a photodetector to give the normal anticipated change in plume shape. Then, a collapse of the flame or rapid flare-up would provide a sharp increase in signal output that can be used to terminate engine thrust. Engines operating below calibrated pressure, such as Engine 2 on the SA-2 flight, would be permitted to continue operating. Such a scheme is sensitive to engine characteristics and responds sufficiently rapidly to shut down engine operation before the malfunction has endangered vehicle structual integrity.

Conclusion

The preceeding remarks are intended to emphasize to you two important areas of automatic checkout; (1) in-flight dynamic checking as an extension of pre-flight procedures and (2) image techniques as a supplement to digital techniques for data handling. The increased standard-

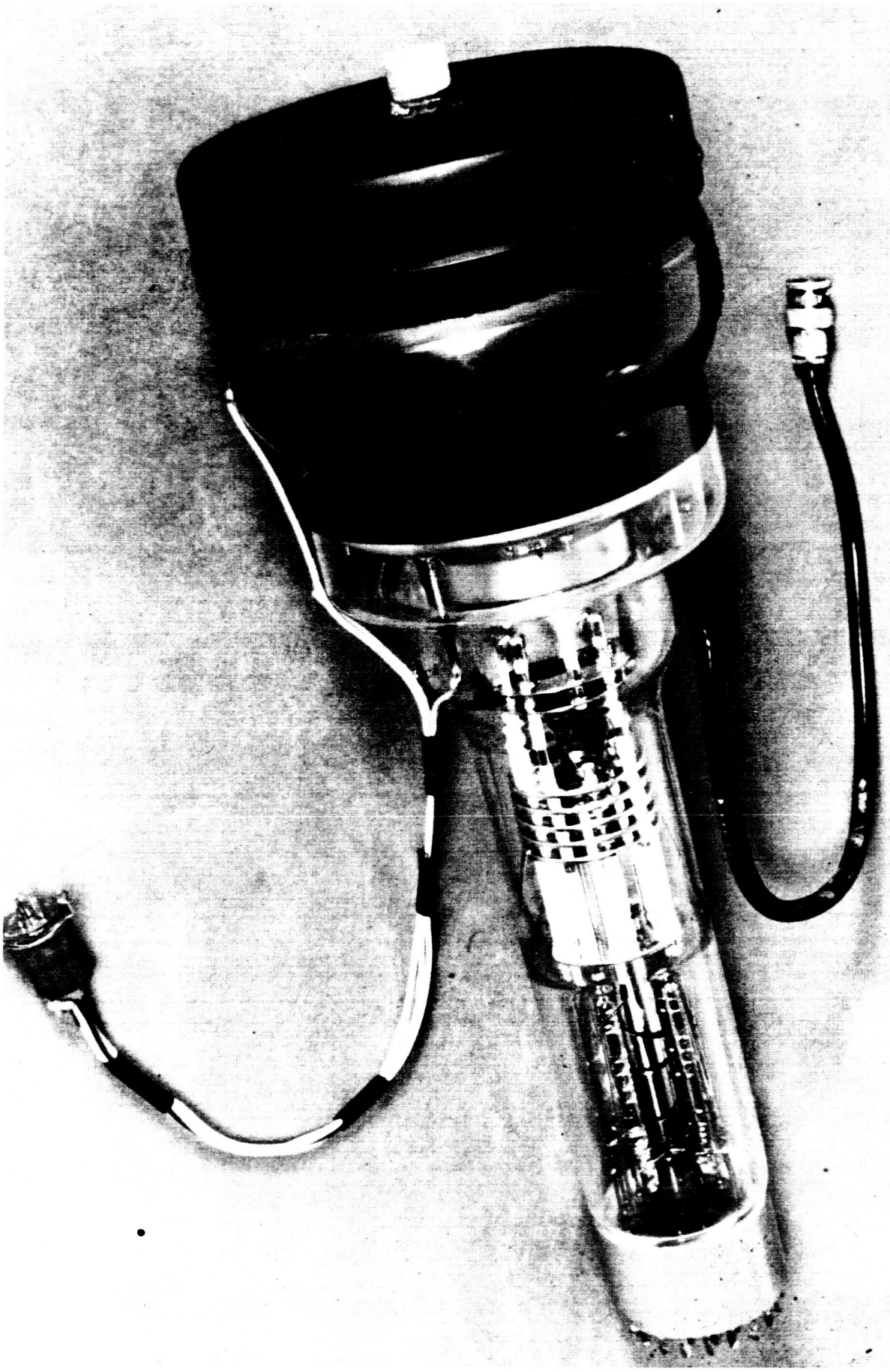


Figure 8.

ization of SATURN ground checkout hardware through use of the RCA 110 computer and of PCM telemetry for data acquisition during pre-launch phases makes it logical that pre-launch automatic checkout procedures be extended to in-flight system management. Also pre-flight image techniques, such as infra-red or fluorescent paint to isolate equipment hot spots or phosphor covered fiber optics or engine test stand monitoring, are proving so valuable that it is reasonable to look to image techniques as an important avenue to solving in-flight management system problems. I believe your efforts to develop these areas of checkout will meet with much success.

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PRECISE ESTIMATES OF SYSTEM DYNAMICS FROM NORMAL OPERATING RECORDS

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ARTHUR E. MACE, Battelle Memorial Institute.

Dr. Mace obtained his BA degree (Amhurst College) and his PhD degree (University of Chicago). Since joining Battelle in 1956, Dr. Mace has been primarily engaged in engineering applications of probability and statistics. His work has included experience in stochastic processes, experimental design, error analysis, statistical inference, and the use of automatic computers for statistical analysis. At present he is engaged in the development of probabilistic models to represent deterioration and failure processes in electronic components and systems in the formulation of statistical procedures for their estimation from experimental data so as to provide the basis for maintenance or replacement policy. Dr. Mace has written technical papers that have been published in the Harvard Review of *Economics and Statistics* and *Industrial Quality Control* (in press). He is a member of the American Statistical Association, American Society for Quality Control, Econometric Society, and the American Economic Association. Present position: Assistant Chief in the Mathematics and Theoretical Physics Division.

THE SYSTEMS APPROACH TO AUTOMATIC CHECKOUT

PART II

John J. Coleman

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Mr. Coleman received his BS in physics (Rensselaer Polytechnic Institute) and an MS in applied mathematics (Brown University). He has spent over 15 years of professional and managerial experience on national security problems in the fields of long-range strategic strike and counterstrike forces; global systems for detecting nuclear explosions in various environments; studies on systems reliability, maintainability, spares logistics, readiness and advanced checkout techniques, and on operational analyses on the system design and cost effectiveness of national space programs, both military and civilian. Mr. Coleman is also a lecturer in Systems Engineering/ Operations Research at the University of Southern California, and has published and delivered 36 technical papers. Present position: Staff Engineer, Aerospace Systems.

INTEGRATED VEHICLE CHECKOUT SYSTEM

ERROR ANALYSIS

R. J. Allen

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Precise Estimates of System Dynamics from Normal Operating Records

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This paper has three objectives: (1) to review certain theoretical developments in control systems engineering and statistics which appear to provide a rational basis for the checkout of physical systems, (2) to describe six laboratory experiments in which statistical procedures have been used to estimate the operational capability of rather diverse engineering systems, and (3) to indicate how these procedures can be used to conduct inflight and prelaunch checkout of aircraft and spacecraft systems.

Two recent independent studies, one by Ramo Wooldridge*, the other by Battelle Memorial Institute**, indicate that the checkout procedure can be greatly simplified. These studies have expressed concern over the difficult task involved when ground personnel are required to integrate the huge amount of test information produced by conventional ground checkout activities. And they have expressed doubts as to whether inflight checkout of aircraft and spacecraft systems can be meaningfully performed by displaying to flight crews a galaxy of meter readings or a complicated matrix of go, no-go warning lights. Both of these studies recommend that the checkout procedure should be based on a well-defined mathematical model of system dynamics. These studies

* Ramo Wooldridge, Final Report on Study of Fault Location and Prediction Techniques Leading to Plans for Automatic and Dynamic Testing of Military Ground Equipment, Contract AF 30(602)-1997 (February 15, 1960), Rome Air Development Center, Air Research and Development Command, United States Air Force.

** Battelle Memorial Institute, Final Report on the Formulation of Automatic Checkout Techniques, Contract AF 33(616)-7761 (March, 1962), Aeronautical Systems Division, Director of Aeromechanics, Flight Accessories Laboratory, Wright-Patterson Air Force Base, Ohio. Technical Documentary Report No. ASD-TDR-62-291.

claim that the test data to be acquired by the checkout operation should be organized so as to produce a simple, unequivocal assessment of the operational capability of the system.

Developments in the theory of control systems engineering within the past thirty years* suggest that an orderly analysis of the dynamics of an engineered system can be based on the concept of transfer functions. Just what a transfer function is can be explained most easily in terms of a one-input one-output system in which the time response of the output to an arbitrary input can be represented by a linear differential equation with constant coefficients. To explain the transfer function for this system, we let $r(t)$ denote the input variable to this system as a function of time and $c(t)$ denote the output variable as a function of time. Making use of integral transforms, we define $R(s) = \int_0^\infty r(t)\exp(-st)dt$ and $C(s) = \int_0^\infty c(t)\exp(-st)dt$ as the Laplace transforms of the input and output functions where s is a complex variable. Then the transfer function, $H(s)$, is defined as the ratio of these two Laplace transforms, $H(s) = C(s)/R(s)$.

For simple time-invariant linear systems of the type described, the transfer function is independent of the particular operating level of the input variables. More generally, however, for real physical systems with nonlinearities, the transfer function will itself be a function of

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* Gardner, M. F. and Barnes, J. L., Transients in Linear Systems, (New York: John Wiley and Sons, 1942) and Del Toro, Vincent and Parker, S. R., Principles of Control Systems Engineering, (New York: McGraw-Hill, 1960).

the levels of the input variables. So for purposes of assessing the operational capability of real physical systems, transfer functions should be evaluated in the immediate vicinity of the mean operating levels of all the input variables.

Still more generally for multiple-input multiple-output systems having n inputs and m outputs, the complete dynamics of system operation can be reasonably well approximated in the vicinity of its mean input operating levels by an n x m matrix of transfer functions:

$$\begin{vmatrix} H_{11}(s) & H_{12}(s) \cdots H_{1m}(s) \\ H_{21}(s) & H_{22}(s) \cdots H_{2m}(s) \\ \vdots & \vdots \quad\quad \vdots \\ H_{n1}(s) & H_{n2}(s) \cdots H_{nm}(s) \end{vmatrix} ,$$

where $H_{ij}(s) = C_j(s)/R_i(s)$. Both the Ramo Wooldridge and Battelle studies claim that the checkout procedure can be greatly simplified if checkout activities are directed toward acquiring the empirical data necessary to estimate the transfer functions of systems and their components.

There are three common test procedures for estimating transfer functions which have sometimes been incorporated in the checkout activity.

The classical method is to subject the physical system to a sinusoidal input of unit amplitude and given frequency and to record the steady-state amplitude and phase change in the output at this frequency. Then the frequency response is explored by a sequence of tests at different frequencies. A second method is to subject the physical system to a unit-impulse input (ideally a Dirac delta function) and to record the resulting impulse response as a function of time. The frequency response is calculated as the Fourier transform of the resulting impulse response. A third method, which includes the first two as special cases, is to subject the physical system to an arbitrary known input (ideally one for which a Fourier transform exists) and to record the resulting response as a function of time. The frequency response is calculated as the ratio of the Fourier transform of the response to the Fourier transform of the input.

The principal difficulty with these common test procedures for estimating transfer functions is that they usually overtax the idealized mathematical model of system dynamics by exercising the system one variable at a time outside the immediate vicinity of that configuration of system inputs associated with their mean normal operating levels. Use of these common test procedures for estimating transfer functions in the dynamic testing of physical systems has further created other problems: (1) difficulties in exciting the system by the desired inputs, (2) difficulties arising because of the existence of extraneous noise inputs to the system, (3) difficulties arising because of errors in measuring the inputs and outputs, and (4) computational difficulties.

Developments in the theory of random processes and statistical estimation within the past thirty years* suggest that transfer functions can be estimated from normal operating records of a system if these records are sensitive enough to exhibit random noise components. Just how system transfer functions can be recovered from the normal operating records of a physical system can be explained most easily in terms of a one-input one-output time-invariant linear system. Such a simple system has but one transfer function. For such a system the response to an arbitrary input function is given by the convolution integral:

$$c(t) = \int_{-\infty}^{\infty} h(v)\, r(t-v)dv \quad ,$$

where $r(t)$ and $c(t)$ denote the input and output functions and $h(v)$ denotes the system unit-impulse response. Now when the system is excited by random disturbances, we can regard $r(t)$ and $c(t)$ as mean-zero stationary random disturbances with a 2 x 2 matrix of covariance functions:

$$\begin{vmatrix} \varphi_{rr}(\tau) & \varphi_{rc}(\tau) \\ \varphi_{cr}(\tau) & \varphi_{cc}(\tau) \end{vmatrix} \quad ,$$

where $\varphi_{ij}(\tau) = \lim_{T\to\infty} (1/2\pi) \int_{-T}^{T} x_i(t)x_j(t+\tau)$, with τ being a continuous time of displacement independent of t. Instead of the convolution integral, we could write:

$$\varphi_{rc}(\tau) = \int_{-\infty}^{\infty} h(v)\, \varphi_{rr}(\tau-v)dv.$$

Making use of integral transforms, we could replace the matrix of covariance functions by a 2 x 2 matrix of their Fourier transforms:

* Wiener, Norbert, Extrapolation, Interpolation and Smoothing of Stationary Time Series, (New York: MIT Technology Press and John Wiley and Sons, 1950) and Lee, Y. W., Statistical Theory in Communication, (New York: John Wiley and Sons, 1960).

$$\begin{vmatrix} \Phi_{rr}(\omega) & \Phi_{rc}(\omega) \\ \Phi_{cr}(\omega) & \Phi_{cc}(\omega) \end{vmatrix} ,$$

where $\Phi_{ij}(\omega)=(1/2\pi)\int_{-\infty}^{\infty} \varphi_{ij}(\tau)\exp(-j\omega\tau)d\tau$, with ω being the fundamental angular frequency (in radians per time unit). Then instead of the convolution integral, we could write:

$$\Phi_{rc}(\omega) = H(\omega)\ \Phi_{rr}(\omega) ,$$

where $H(\omega) = \int_{-\infty}^{\infty} h(v)\exp(-j\omega v)dv$ denotes the Fourier transform of the unit-impulse response and is the frequency response of this system.

The Fourier transforms of the covariance functions are called power spectra. So we may say that the frequency response of this system can be recovered from normal operating records as the ratio of the input-output cross-power spectrum to the input power spectrum, that is:

$$H(\omega) = \Phi_{rc}(\omega)/\Phi_{rr}(\omega) .$$

For simple time-invariant linear systems of the type described, the frequency response provides a complete description of the operational capability of the system. When the input to such a system has a known spectrum of disturbances, then the spectrum of disturbances in the output will be given by the relation:

$$\Phi_{cc}(\omega) = \left| H(\omega) \right|^2 \Phi_{rr}(\omega) .$$

Further if there is an extraneous noise input to the system which is independent of the recorded input function, then the proportion of the spectrum of disturbances in the output which will be explained by this relation will be given by the so-called coefficient of linear coherence:

$$\left[\gamma_{rc}(\omega)\right]^2 = \left|\Phi_{rc}(\omega)\right|^2 / \Phi_{rr}(\omega)\Phi_{cc}(\omega) \quad .$$

Now the frequency response is a complex function of frequency and can be represented in polar coordinates as the product of two terms:

$$H(\omega) = G(\omega)\exp\left[jP(\omega)\right] ,$$

where $G(\omega)$ is the gain of the system response as a function of frequency and $P(\omega)$ is the phase angle of the system response as a function of frequency.

About six years ago statisticians at Princeton University developed a practical computational procedure for estimating system frequency responses from finite-length normal operating records of a physical system.* The procedure requires that:

(1) the inputs and outputs of a physical system be identified from a schematic block diagram of the system;

(2) these inputs and outputs be sensed during normal system operation by appropriate measuring instrumentation; and

(3) simultaneous time-sampled records of these inputs and outputs be obtained with a prescribed sampling interval.

Then procedure then produces:

(1) estimates of the average gain and average phase angle of each frequency response over a sequence of equally spaced nonoverlapping frequency intervals;

* Blackman, R. B. and Tukey, J. W., The Measurement of Power Spectra, (New York: Dover Publications, 1958) and Goodman, N. R., On the Joint Estimation of the Spectra, Cospectrum and Quadrature Spectrum of a Two-Dimensional Stationary Gaussian Process, Scientific Paper No. 10, Engineering Statistics Laboratory, New York University, 1957 (Ph.D. Thesis, Princeton University).

(2) estimates of the corresponding coefficients of linear coherence; and

(3) measures of the precision of these estimates.

The remarkable feature of the computational procedure is that by judicious choice of the duration of the input and output records and by judicious choice of the length of the sampling interval, it is possible to produce estimates of system frequency responses with arbitrarily predetermined resolution and precision. In other words, by appropriate design of data-taking procedures we can jointly control:

(1) the amount of smoothing involved in estimating the average frequency response in nonoverlapping frequency intervals; and

(2) the sampling variability of these estimates, that is, the repeatability with which estimates of the system frequency response could be obtained in successive applications of the procedure.

The prospect of incorporating these procedures for estimating system transfer functions from normal operating records into the checkout activity looks particularly inviting. And it appears to be worthwhile to consider certain laboratory experiments in which these procedures have been used to characterize the operational capability of rather diverse engineering systems.

Experiment No. 1 was conducted at the Stamford laboratories of the American Cyanamid Company in Connecticut in order to determine the

operating characteristics of a continuous input-output mixer, with water used as a flow agent and temperature used as a tracer.* Water was continuously fed into a glass vessel with reasonably good thermal insulation, was continuously stirred in the vessel, and was allowed to overflow to a sink. Inlet temperature was controlled with an electrical immersion heater interposed in the water feed line. The frequency response of interest was that between the inlet temperature and outlet temperature of the water, when transformer settings controlling the immersion heater were subjected to a precomputed noise pattern. Empirically determined gain and phase plots were compared with the theoretical response based on the differential equations of the process. In general, there was good agreement between theory and experiment, but at low frequencies the empirically determined gain was less than expected. The coefficient of linear coherence was sometimes as low as 0.8 (particularly at low frequencies), indicating the presence of some disturbance not reflected in the simple differential equation of the process.

Experiment No. 2 was conducted at the research laboratories of the Foxboro Company in Massachusetts to determine the operating characteristics of a heat exchanger.** Mains water was allowed to flow into a water heater where it was heated by steam at 40 pounds per square

* Goodman, N. R., Katz, S., Kramer, B. H., and Kuo, M. T., "Frequency Response from Stationary Noise: Two Case Histories", Technometrics 3:245-268 (May, 1961).

** Florentin, J. J., Hainsworth, B. D., Reswick, J. B. and Wescott, J. H., "Correlation Analysis of a Heat Exchanger", Proceedings of the Joint Symposium on Instrumentation and Computation in Process Development and Design held in London, England, May 11-13, 1959, pp 18-28 (published by the Institution of Chemical Engineers); Westcott, J. H., "The Parameter Estimation Problem", Proceedings of the First International Congress of the International Federation of Automatic Control held in Moscow, Russia, 1960 (published in Automatic and Remote Control, Volume II, pp 779-787); and Jenkins, G. M., "An Example of the Estimation of a Linear Open Loop Transfer Function", Technometrics 5:227-245 (May, 1963).

inch. Normally this system had an adaptive-controlled steam supply to regulate the outlet water at a nominal temperature of 150 degrees Fahrenheit; but for purposes of this experiment the controller was disconnected for a 10-minute period to obtain open-loop operating records. The frequency response of interest was between the inlet water flow rate and the outlet water temperature. Empirically determined gain and phase plots were examined for consistency with the expected form of the theoretical response based on the differential equations of the process. The empirically determined phase plot was consistent with the theoretical form expected; but the peak or resonance in the empirically determined gain plot could not be explained by a single time constant. The coefficient of linear coherence was only as high as 0.6 at low frequencies; greater precision in the frequency response at high frequencies would have been obtained if the inlet flow rate had been probed with broadband stationary noise.

Experiment No. 3 was conducted by research workers at the University of Oklahoma to determine the operating characteristics of a continuous stirred tank chemical reactor used as a heat exchanger (no reaction was carried out).* Only a process of heat exchange took place in the reactor between the coolant coils and the reactor material. For purposes of this experiment both the inlet fluid and the coolant fluid were water. Two frequency responses were of interest: the response of the reactor outlet temperature to the coolant flow rate and the response of the reactor outlet temperature to the reactor inlet temperature. In one experiment the coolant flow rate was varied by probing it with stationary random noise. Empirically determined gain and phase plots were compared both with the theoretical response based on the differential equations

* Gallier, P. W., Sliepcevich, C. M., and Puckett, T. H., "Some Practical Limitations of Correlation Techniques in Determining Process Frequency Response", Process Dynamics and Control, Chemical Engineering Progress Symposium Series Vol. 57, No. 36 (1961) pp 59-68 (published by the American Institute of Chemical Engineers).

of the process and with an experimental response obtained by a direct sinusoidal test. In general, there was excellent agreement between empirically determined plots and both the theoretical and sinusoidal responses. Only at high frequencies above the frequency of 0.08 cycles per second do the plots begin to differ. In a second experiment both the coolant flow rate and the reactor inlet temperature were varied by probing them with stationary random noise. But in this second experiment the two input variables were so highly intercorrelated that their individual frequency responses could not be separated.

Experiment No. 4 involved a nonlinear chemical reactor which was simulated on a digital computer at the University of Minnesota.* The particular reactor was a continuous stirred tank reactor supporting an exothermic second order reaction and cooled by the passage of water through a jacket. Two molecules of the reagent were presumed to react irreversibly to yield a product and heat. There were two frequency responses of interest: the response of the outlet reagent concentration to the inlet temperature of the reactant mixture and the response of the outlet reagent concentration to the inlet reagent concentration. In one experiment the simulated inlet temperature of the reactant mixture was varied by imposing stationary noise on its steady state value of about 170 degrees Fahrenheit. The empirically determined frequency response gave a reasonably good approximation to the theoretical response based

* Tierney, J. W., Homan, C. J., Nemanic, D. J., and Amundson, N. R., "The Digital Computer as a Process Controller", Control Engineering 4:166-175 (September, 1957); Aris, R. and Amundson, N. R., "Statistical Analysis of a Reactor:Linear Theory", Chemical Engineering Science, 9:250-262 (1958); Homan, C. J. and Tierney, J. W., "Determination of Dynamic Characteristics of Processes in the Presence of Random Disturbances", Chemical Engineering Science, 12:153-165 (1960); and Goodman, N. R., Katz, S., Kramer, B. H. and Kuo, M. T., "Frequency Response from Stationary Noise:Two Case Histories", Technometrics, 3:245-268 (May, 1961).

on the linearized differential equations of the process for a suitable compromise between resolution and stability in the estimates. In a second experiment the simulated inlet reagent concentration was varied by imposing stationary noise on its steady state value of 1 pound-mole per cubic foot, with trials at various noise amplitudes. The agreement between theory and experiment was not very good for this highly nonlinear chemical reactor except possibly for low amplitude noise levels. For the lowest noise level, however, a characteristic peak near 0.001 cycles per second was made evident.

Experiment No. 5 involved a study of the rolling action of a ship model in response to artificially generated water waves.* An attempt was made to determine the amplitude and phase relations of the ship motions in response to irregular head seas. Empirically determined gain and phase plots were constructed; and the gain plot was compared with that obtained in response to regular sinusoidal waves. Preliminary results gave low estimates of linear coherency and failed to produce very good agreement. Correction of records for delays in recording the input and output by time shifting the records raised estimates of coherency and improved agreement. A fairly large bias due to smoothing still remained at the peak of the amplitude gain.

* Darzell, J. F. and Yamanouchi, Y., The Analysis of Model Test Results in Irregular Head Seas to Determine the Amplitude and Phase Relations to the Waves, Stevens Institute of Technology Report 708 (1958); Darzell, J. F. and Pierson, W. J. Jr., The Apparent Loss of Coherency in Vector Gaussian Processes Due to Computational Procedures With Application to Ship Motions and Random Sea, Technical Report of the College of Engineering Research Division, Department of Meteorology and Oceanography, New York University (1957); and Akaike, Hirotugu and Yamanouchi, Yasufumi, "On the Statistical Estimation of Frequency Response Function", Annals of the Institute of Statistical Mathematics (Tokyo) 14:23-56 (1962).

Experiment No. 6 was conducted at the Isuzu Motor Company in Japan in order to determine the operating characteristics of an automobile frame suspension.* Records were obtained of the oscillations of the front axle and the frame of an automobile traveling over a paved road. Empirically determined gain and phase plots were constructed; and the gain plot was compared with that obtained in response to sinusoidal inputs. Good agreement in the estimate of the amplitude gain was obtained only for long duration records and high resolution. Under these conditions the existence of sharp peaks in the gain around 9 cycles per second was made evident.

The results of these six experiments provide a qualified acceptance of the validity of statistical procedures for recovering the system frequency response from normal operating records. As experience with specific physical systems is gained, it would appear that these procedures can provide a logical basis for monitoring the operational capability of these systems and alerting operating personnel as to the necessity of maintenance and repair.

In order to use these procedures with specific aircraft and spacecraft systems, instrumentation would be required: (1) to sense the input and output functions of the system, and (2) to time-sample and record digitized values of these input and output functions with very short sampling intervals. In addition a digital computer would be required to perform the necessary computations after a record of sufficient duration had been obtained.

* Kanesige, I., "Measurement of Power Spectra of Vehicle Vibration and Vehicle Road Roughness", Proceedings of the Tenth Japan National Congress for Applied Mechanics (1960) pp 371-374; and Akaike, Hirotugu and Yamanouchi, Yasufumi, "On the Statistical Estimation of Frequency Response Function", Annals of the Institute of Statistical Mathematics (Tokyo) 14:23-56 (1962).

Even with the necessary instrumentation and computing equipment, the task of adapting these procedures to specific aircraft and spacecraft systems so that they produce accurate information appears to require painstaking engineering effort. But the benefits which can accrue through their successful application are substantial. By integrating all the relevant information about the operational capability of a system in a few simple gain and phase plots, these procedures would provide operating personnel of aircraft or spacecraft systems with a direct, unequivocal assessment of the operating characteristics of their system.

THE SYSTEM APPROACH TO AUTOMATIC CHECKOUT

PART I

Robert A. Kirkman

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Mr. Kirkman studied electrical engineering (C.C.N.Y.), graduated with a certificate in communications engineering (RCA Institute Resident School), and has done extensive graduate work in microwaves, mathematics, control systems, and space technology (Rutgers University), (U.C.L.A.). He has 23 years of experience in commercial and military electronics in the fields of ground radars and automatic weather stations; participated in early White Sands firings; airborne beacons, data-handling systems, and computers. His systems experience includes project engineering, program management and design integration for the Atlas missile; the F-106 and F-108 interceptors; high-speed, internally programmed, automatic checkout equipment design for Wizard, Nike-Zeus, Skybolt, Pershing and Apollo; and he is the author of several papers on systems testability, checkout, and reliability. Mr. Kirkman is a Senior Member of the IEEE and of several of its Professional Groups. He has held several IRE offices and is a Past Chairman of the San Diego Section. Present position: Minuteman Project Engineer on Ground Equipment.

THE SYSTEM APPROACH TO AUTOMATIC CHECKOUT

PART III

M. C. Peterson

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Mr. Peterson received the BEE degree in electronics in 1950 (University of Southern California). He did further graduate work in engineering and business administration from 1952 to 1961 (U.C.L.A.). From 1950 to 1959, he was employed by Bendix Aviation and in 1959 he joined Space Technology Laboratories as a member of the technical staff, working on Able space-probe system test and launch control equipment development. He is presently engaged in preliminary design, development, and evaluation of semiautomatic systems checkout equipment for space-probe and ballistics-weapon system programs. Mr. Peterson has participated in the courses given at U.C.L.A. on Ballistic Missiles and Space Vehicles, and in Automatic Checkout. Present position: Head, Systems Engineering Section, Support Systems Department.

INTEGRATED VEHICLE CHECKOUT SYSTEM ERROR ANALYSIS

by

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ABSTRACT

This paper describes some of the findings in performing an error analysis and the techniques that were used to minimize these errors in association with an Intercontinental Ballistic Missile complex. Presented are the following:

1. A technique employing a one-third page combinational flip chart, used to assist in the mammoth task of analyzing error-producing interface circuitry, site cabling, and checkout functional modules.
2. Graphic illustration of how phase shifted even harmonics combine with the fundamental to produce wave asymmetry.
3. Measurement errors due to wave distortion attributed to the checkout system peak, synchronous, and phase detectors.
4. Methods for minimizing these errors by incorporating a special harmonic comb filter with essentially zero phase shift and unity gain.
5. Errors caused by paralleling test point selector relays and methods for minimizing these errors.
6. Discussion of the cause of an intermodulation problem encountered.

The paper is concluded with a brief summary of the loop analysis performed of the integrated checkout system, site cabling, and various vehicle subsystems.

INTRODUCTION

Automatic checkout systems are employed to verify the flight readiness of such systems as Intercontinental Ballistic Missiles and military aircraft. These checkout systems must be designed to be capable of performing the many required functions with accuracy exceeding those of the various subsystems being verified. With the advances in the precision of the present-day vehicular subsystems, the required checkout systems capabilities are extremely stringent. The accuracy requirements for producing the many and varied stimuli and evaluating response signals are constantly pushing the state-of-the-art. Therefore, the interconnecting cabling and interface load impedances must be considered and not allowed to degrade the checkout system accuracy. Of equal importance is the necessity to know the general characteristics of the signals being verified and to account for accuracy degradation in checkout system detector modules in the event measurements are being performed on distorted waves.

This paper describes some of the general findings in performing an error analysis and the techniques that were used to minimize these errors in association with an Intercontinental Ballistic Missile complex. This analysis covered (1) the automatic checkout equipment; (2) site cabling; (3) missile subsystem interface circuitry; and (4) launch control equipment. This study led to improving and specifying the stimuli and measurement accuracy capabilities of the automatic checkout system, including the associated interface cabling. One of the more important findings during this analysis was the effect upon the accuracy of the checkout system measurement capabilities when the checkout system was supplied a distorted wave from the subsystem under test or from the ground power unit.

UNIQUE COMBINATIONAL 1/3 PAGE FLIP CHARTS

The missile complex that was analyzed employed more than a thousand interconnecting copper paths forming the site cabling between the checkout equipment and various subsystems under test. The checkout equipment performed a large number of different functions and there

were many combinations of interface points and circuitry associated with the many subsystems under test. To draw functional flow diagrams for each of the many possible combinations and to determine associated loop errors for each would have been a mammoth task.

To simplify the task, an 11 x 17 inch spiral brochure was assembled with the spiral along the 17-inch top. The pages were multi-colored cover-stock cut into three sections; the turning of pages of each section was independent of the other two. On the left-hand section was drawn the automatic checkout system interface circuitry and associated functional blocks contributing to the overall functional accuracy. The color of the pages denoted the checkout system function such as voltage stimuli and measurement, timing, transfer function analysis, etc.

On the center section were drawn the various combinations and types of interconnecting wires and pertinent cable characteristics. For example, as many as 11 copper paths using unshielded wires were employed to perform a multi-valve timing function employing five counters in the checkout equipment and verifying the time to open and close combinations of the boosters and sustainer engine fuel and head suppression valves and associated control circuitry. Other cabling included shielded wires, low resistance copper paths, and coax cabling.

The right-hand section contained the interface circuitry and associated functional blocks describing the various subsystems under test. The color coding employed denoted whether the subsystem under test was aboard the missile, in the launch control equipment, or in other ground support equipment.

By employing this technique and indicating the tolerances associated with each functional block and interface component, it was possible to calculate the loop errors of the overall integrated checkout system/cabling/system-under-test by selecting the appropriate combination of these three one-third page flip charts.

STUDY APPROACH

Automatic Checkout System

The first phase of the analysis was associated with the Automatic Checkout System. The interface circuitry and pertinent portions of the block diagrams associated with the many and various functions were drawn. Some of these functions included:

a. Discrete signal control and monitoring, where time is not a factor.

b. Controlled timing functions, where discrete "Start" signal is applied at t_o and discrete events are measured at t_1, t_2, ... t_n.

c. Steady state voltage function (relative and absolute).
   (1) D-C stimuli; d-c measurement.
   (2) 400-cycle constant amplitude (single or dual channel) stimuli; single channel measurement function with or without 400-cycle harmonic filter employing peak detection or synchronous detection.
   (3) Other frequency constant amplitude measurement.

d. 400-cycle phase shift measurement.

e. Transfer function analysis employing low frequency suppressed carrier modulated 400 cps stimuli and measuring in-phase or quadrature response components.

f. Step function stimuli.
   (1) 0 to preselected d-c levels; selected d-c to 0 level.
   (2) 0 to preselected a-c level; selected a-c level to 0.

g. Resistance measurement.

h. Frequency measurement.

i. Other.

Since accuracy is not a concern during discrete signal control and monitoring functions where time is not a factor, all circuits associated with this function were eliminated. When analyzing the various controlled timing and discrete event measuring functions, consideration was given to relay driver and relay closing delays.

Also delays associated with logical circuitry starting and stopping counter registers employed were determined. When analyzing voltage measurement functions, leakage associated with the many parallel relays used for test point selection was considered. The effect that leakage has on the input impedance of the checkout system was determined and included along with assigned stimuli and measurement tolerances on the functional block diagram drawn on the left-hand portion of the flip-chart brochure.

The second phase of the analysis was associated with the missile subsystems. The interface circuitry and functional blocks of the various single-ended and test loops were determined. A few examples are:

a. Flight control subsystem
   (1) Noise test: nulling of the torque amplifier driving a displacement gyro and measuring for a-c noise on the output of the displacement gyro emitter follower.
   (2) Engine static gain test: supplying an a-c 400-cycle voltage to the input of the demodulator and measuring the 400-cycle response voltage from the engine position feedback transducer.
   (3) Gyro torquing gain test: supplying a relative 400-cycle voltage for a period of a pre-determined number of seconds to the input of the torque amplifier driving an integrating gyro. The amplitude of the voltage out of a signal amplifier is measured as a function of time.

b. Booster and sustainer engine valve timing tests.

c. Missile a-c and d-c power tests.

The required test tolerances of the system under test were indicated on these functional block diagrams drawn on the right-hand portion of the flip-chart brochure. The values of the input impedance and the output impedance were indicated along with the other pertinent information.

Site Cabling

The last phase of the study was divided into two operations:

(1) determining the general characteristics of the worst case condition of the proposed site cabling, and (2) determining the more exacting cabling characteristics where the analysis indicated that the cable characteristic was a limiting or an influencing factor. The characteristics of these various interconnecting copper paths were included in the center section of the flip-chart brochure tying together the checkout system and the various systems under test.

STUDY RESULTS

Some of the more important results of this study were the determination and minimizing of (1) errors introduced when measuring a signal containing harmonic distortion; (2) errors associated with relay leakage of the parallel test point selector relay matrix; and (3) errors caused by low frequency intermodulation.

Errors Caused by Wave Distortion

During the performance verification of a vehicle subsystem, a signal may be supplied to the checkout systems in order to determine the amount of distortion present in that signal; or a signal may be supplied with the assumption that a relatively pure sinusoidal wave is being submitted for an amplitude measurement. It is important to know the magnitude of error associated with the measurement processes involved for various amounts and forms of harmonic distortion.

a. Distortion by combinations of harmonics and d-c offset voltage

Even and odd frequency multiples of the fundamental of a pure sinusodial wave are known as harmonics. Harmonics are inherent in all generators and may be intensified in the secondary of a transformer circuit or other areas of electronic systems. Wave distortion can be caused by harmonics, either in-phase or out-of-phase with the fundamental. Distortion also can be caused by many combinations of harmonics of various amplitudes or by a d-c offset voltage. The effect of even and odd harmonics and d-c offset is quite different:

(1) Even harmonics will distort the wave and may simultaneously introduce wave asymmetry by changing the duration

of one-half of the wave, the amount of this change being dependent upon the phase relationship between the fundamental and harmonics. This wave shape asymmetry carries through a capacitor or to the secondary of a transformer.

(2) Odd harmonics will distort the wave shape, but will not produce an asymmetric wave. The cross-over point, however, of the fundamental may shift. The shift will be the same amount at the zero point and 180° point, and the amount of the shift will be dependent upon the phase relationship of the fundamental and the harmonics.

(3) A d-c offset will produce wave asymmetry with respect to the wave reference, but this type of asymmetry and the d-c offset voltage do not carry through a capacitor or to the transformer secondary.

Wave distortion resulting from even and odd harmonics, both in-phase and out-of-phase with the fundamental, can best be demonstrated by the use of graphic analysis. For illustration purposes, a large amplitude harmonic will be employed. Figure 1a shows the effect of an in-phase second (even) harmonic with an amplitude ratio of 20 percent added to the fundamental. This same second harmonic, if phase-shifted a maximum of 90° as in Figure 1b, will result in the indicated asymmetrical wave. The duration of the first half of a wave with second harmonic distortion will vary between π to $\pi \pm 2\phi$, depending upon the phase relation between fundamental and harmonic. The duration of the second half will simultaneously vary oppositely by the same amount (π to $\pi \mp 2\phi$), maintaining the total wave duration by 2π.

A higher order individual even harmonic will produce similar results as that illustrated for the second harmonic. Combinations of even harmonics, when one or more of these harmonics are out-of-phase with the fundamental, will cause wave asymmetry as illustrated in Figure 1c.

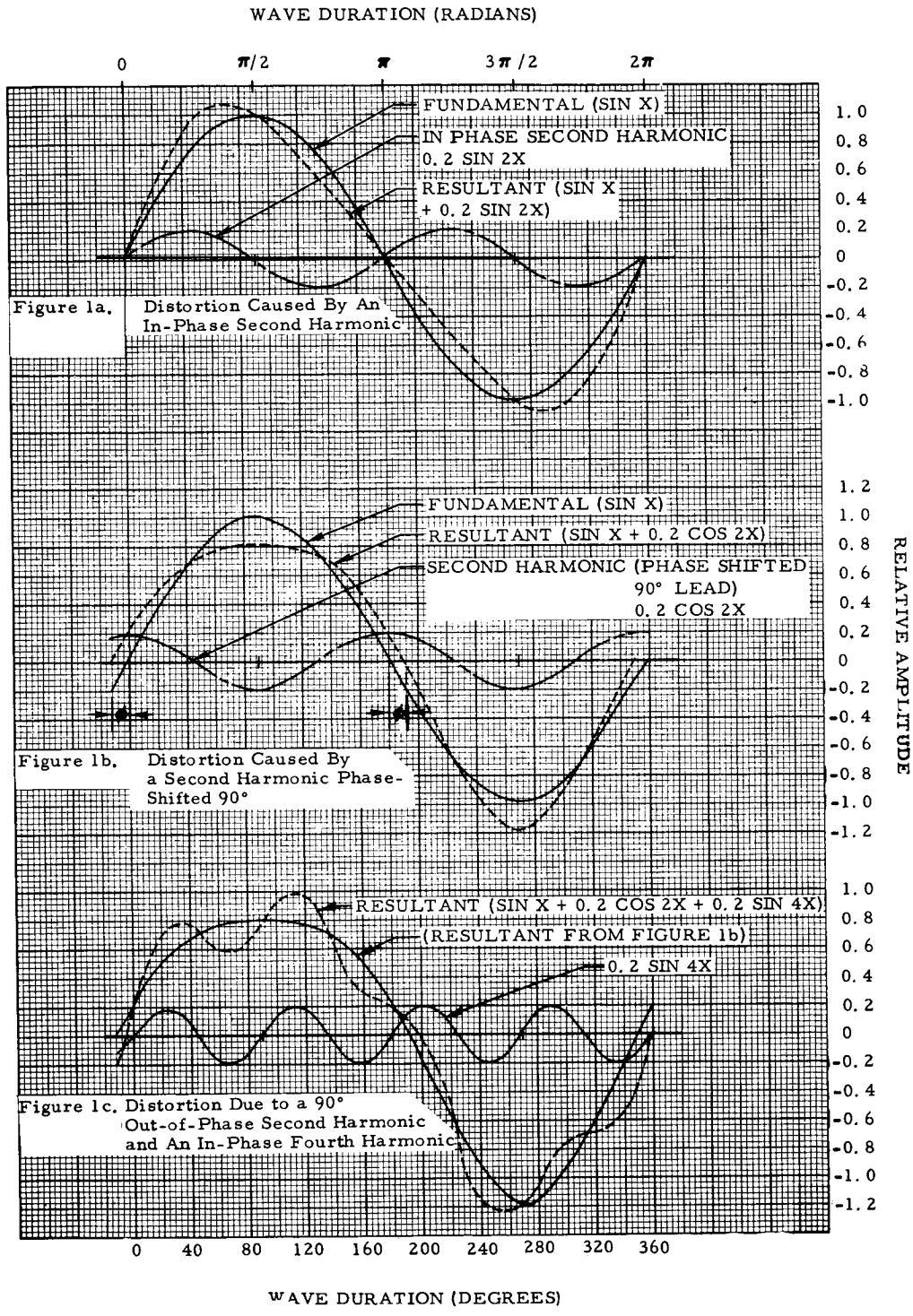

Figure 1a. Distortion Caused By An In-Phase Second Harmonic

Figure 1b. Distortion Caused By a Second Harmonic Phase-Shifted 90°

Figure 1c. Distortion Due to a 90° Out-of-Phase Second Harmonic and An In-Phase Fourth Harmonic

Odd harmonics will cause distortion of the wave, but the distortion in all cases will be symmetrical. This can be seen in Figure 2a which shows an in-phase third (odd) harmonic, and Figure 2b which shows a phase-shifted third harmonic summed with the fundamental. It will be noted in Figure 2b that both the zero and 180° cross-over points are shifted in the same direction by the same amount, θ. Higher order individual and combinations of odd harmonics will produce similar results.

A composite of various harmonics will, of course, result in a complex wave with both even and odd harmonic characteristics. The combination with the fundamental of various harmonics (of proper relative amplitudes) and d-c offset voltages will produce symmetrical square waves, short duration pulses, peaked waves, triangular waves, or sawtooth waves. The combination of a third harmonic, fifth harmonic and seventh harmonic with given amplitudes produce a reasonably perfect symmetrical square wave. Higher order harmonics will sharpen the corners of the square wave. The period of the square wave is equal to that of the fundamental.

Short duration pulses may be formed by combining both even and odd harmonics plus a d-c voltage. The number of harmonics employed is a function of the desired pulse width.*

b. Voltage detector errors

In the process of performing an a-c voltage amplitude measurement, the automatic checkout system produced a d-c voltage proportional to the peak, or 90° point of the a-c voltage amplitude. Detectors incorporated for this conversion are the modules primarily affected by the presence of harmonics. The Peak Detector employed in this system detects the peak value of the positive-going portion of a wave. If an

* Further information on the formation of complex waves and pulses may be obtained by consulting: (1) Department of the Air Force, "Radar Circuit Analysis", AF Manual 52-8, Superintendent of Documents, Washington 25, D.C., pages 6-2 through 6-5; or (2) Terman's Radio Engineers' Handbook.

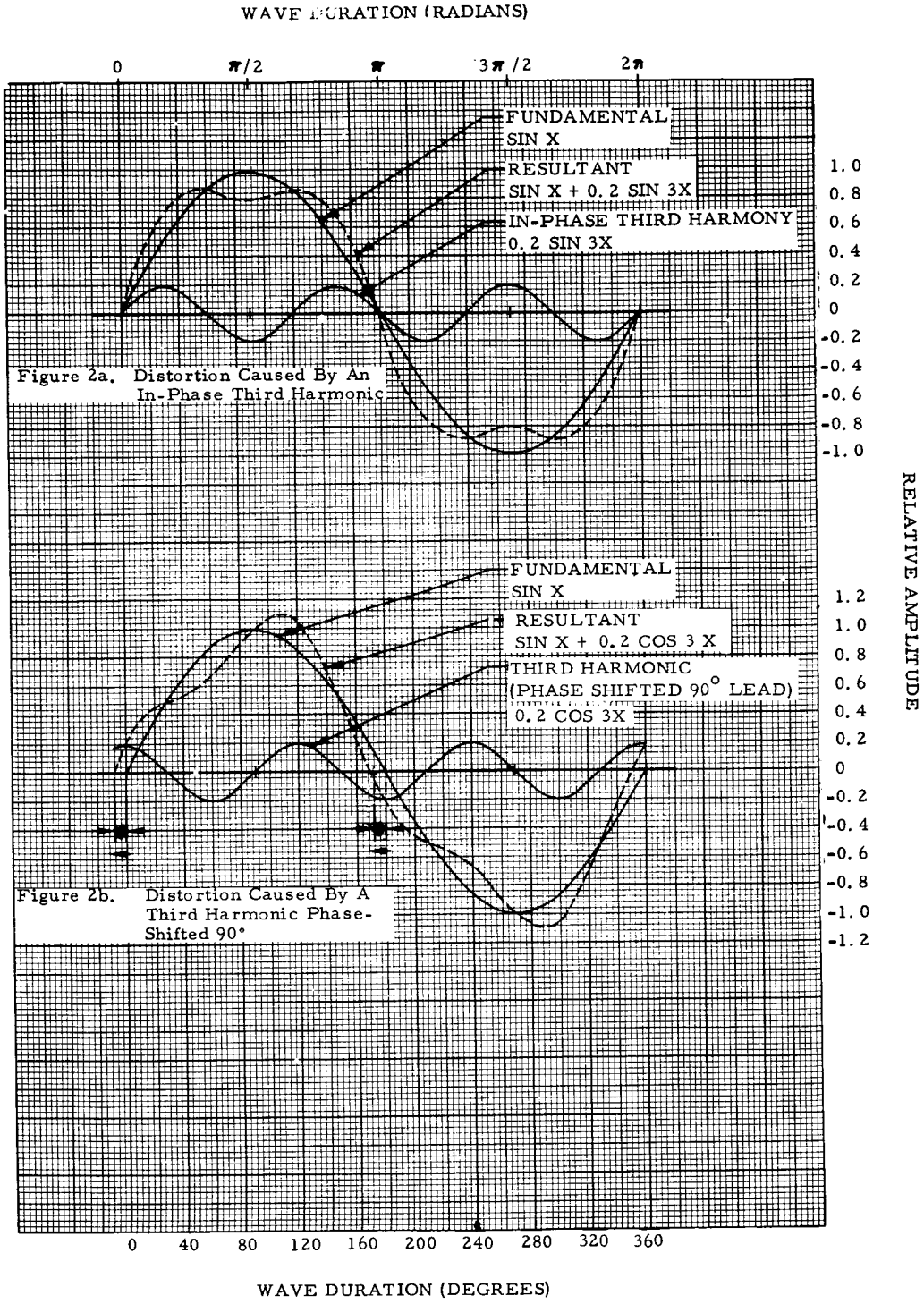

Figure 2a. Distortion Caused By An In-Phase Third Harmonic

Figure 2b. Distortion Caused By A Third Harmonic Phase-Shifted 90°

asymmetric wave, as shown in Figure 1b, is supplied to this type peak detector, the amplitude value measured would be contingent upon which of the peaks were read by the detector as well as the percentage of harmonics present. The amplitude value measured for the distorted wave of Figure 1a, however, would not be contingent upon which peaks were read, but only the percentage of harmonics contained in this wave. The amount of error was obtained by determining the difference of peak values between a pure sinusoidal and the distorted wave, and was expressed as a function of harmonic amplitude and phase relationship with the fundamental.

Also in use with this automatic checkout system is what is called a synchronous detector. This detector is similar to the peak detector in that it produces a d-c voltage output proportional to the peak, providing however that this peak occurs at the 90° point. It will read a voltage amplitude of the signal 90° after a reference voltage (that is also supplied to this module) passes through zero. The one difference, however, from the peak detector is that a positive or negative d-c potential will be produced depending upon whether the signal is in-phase or 180° out-of-phase with the reference. Any wave with harmonic distortion as illustrated in Figures 1 and 2 would introduce errors, the magnitudes of which are dependent upon the amount and type of harmonic distortion and their effect near the 90° point of the fundamental. The portion of the total wave sensed by this type of detector is less than $\pm$ 2° around the 90° point.

If this peak detector with scale factor correction is employed for rms measurements without filtering, the error produced will be a function of the amount and type of distortion. If the filter described later is employed, true rms measurements are possible. It can be shown by performing a Fourier analysis that the rms of a pure fundamental wave and the rms of the same fundamental with 3 percent harmonic distortion differ

by only 0.043 percent in the worst case. This error was found to be small enough to allow the use of an incorporated harmonic filter ahead of the peak detector to measure the true rms value of waves with less than 3 percent harmonic distortion.

c. Phase shift detector errors

This automatic checkout system employs a module for measuring the amount of phase shift of a 400-cycle signal supplied from the subsystems under test in relationship to the site 400-cycles voltage used as a reference. The amount of error when performing a measurement with this module is directly proportional to the total amount of phase shift of the series components in the checkout system ahead of this detector such as the Input Buffer Amplifier, plus errors introduced if the zero crossover is changed by harmonics as in Figures 1b and 2b. The amount of phase shift error due to harmonics is equal to ϕ or θ.

d. Minimizing errors

When harmonic distortion, 60-cps noise, or transients are present, a special filter is employed to minimize the amount of error. This filter may also be employed when making an approximate measurement of the amount of harmonic distortion present in a wave by comparing a measurement taken with and without the filter. A third use of this special filter is for converting a square wave into a sine wave.

Figure 3 is a schematic of this 400-cycle harmonic comb filter with essentially zero phase shift (less than 1^{o} from 393-407 cps). It also has a very minimal controlled insertion loss allowing a small change in an associated feedback circuit of an amplifier to compensate for this loss.

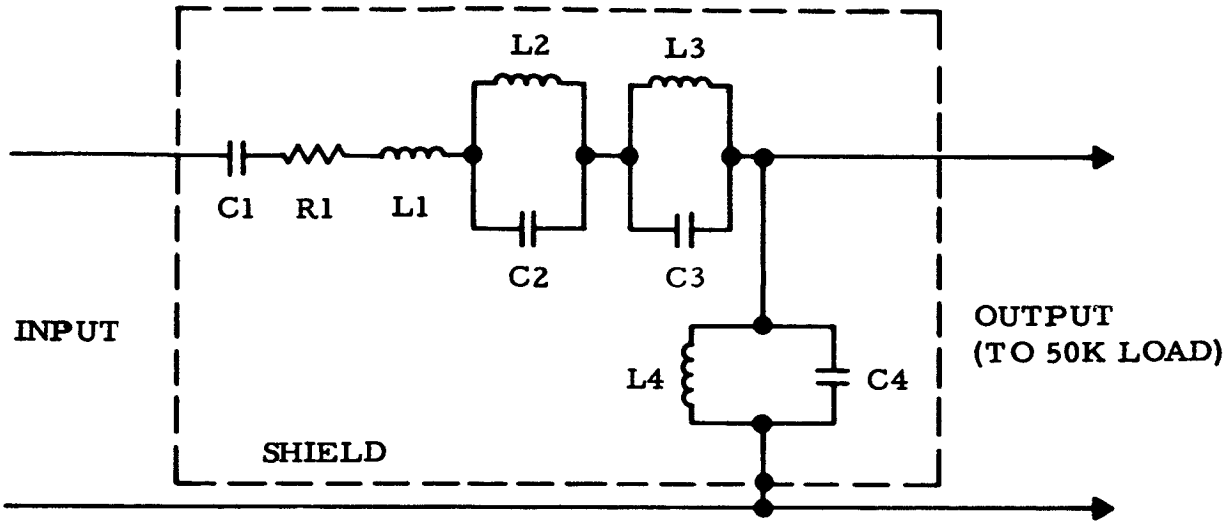

Figure 3. Schematic of Special Zero Phase-Shift, 400 cps Harmonic Comb Filter with Known Precision Gain Close to One.

This filter was designed* to have L2 and C2 antiresonant slightly above 800 cps, L3 and C3 slightly above 1200 cps, and L4 and C4 at 400 cps. The overall series resonance of the combination L2-C2, L3-C3, and L1-C1 is 400 cps. An offset second and third harmonic antiresonance frequency was necessary in order to obtain maximum attenuation from 786 to 814 and 1179 to 1221 cps. R1 was selected as required to obtain the controlled insertion loss at 400 cps. Temperature compensation circuitry was not employed internal to this filter since it was installed in a controlled environment. However, temperature compensation should be added if this filter is employed in an uncontrolled environment because it is quite sensitive to temperature changes.

The characteristics of this filter are shown in Figure 4. It will be noted that the attenuation is greater than 20 db below 100 cps, around 800 cps and 1200 cps, and above

* Filter design was performed under contract to General Dynamics/Astronautics for the Air Force by RCA Data Systems Division, Van Nuys, California. Manufacturers of this filter are: (1) Grinnel Electronics, Glendora, California, (2) Filtron, Culver City, California, (3) Bundy Electronics, Newark, N.J., and others.

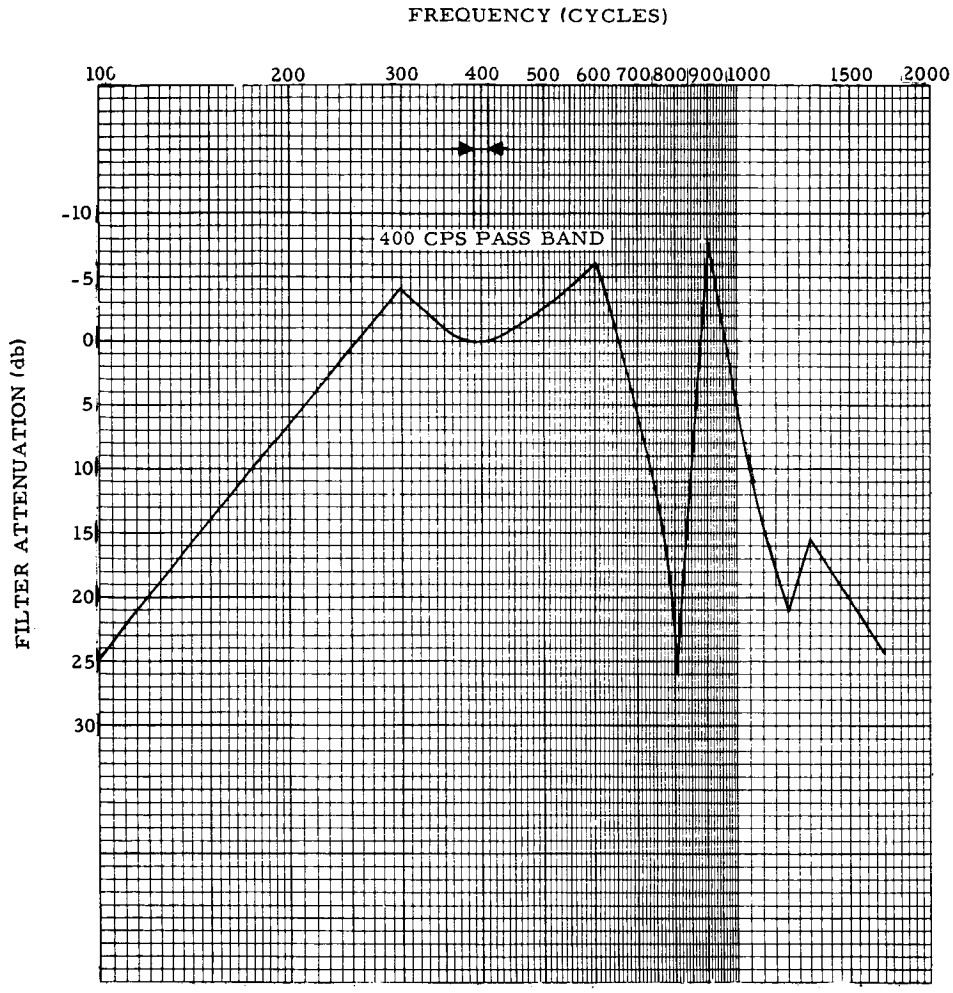

Figure 4. Voltage Output vs Frequency for a Special 400-cps Harmonic Comb Filter with Zero Phase Shift

approximately 1600 cps. This characteristic allowed not only the attenuation of 400-cycle harmonics, but also attenuation of frequencies below 100 cps including the 60-cps power frequency. An expanded section of this curve, around 400 cps, would indicate that it is relatively flat from 393 to 407 cps. Voltage gains were experienced close to 300 cps, 600 cps, and 900 cps. The maximum gain of approximately 2-1/2 was experienced around 900 cps. This is not objectionable, however, since this filter is only used for 400-cps operations.

Errors Caused by Test Point Selector Relays

The various stimuli and response signals are routed through a switching matrix in the checkout system. This switching matrix consisted of several relays in parallel used to route the various stimuli to the system under test and select the proper test point carrying the response from the system under test. In this checkout system, each relay was in parallel with the single relay automatically selected for a particular analog signal measurement. The leakage of a typical open relay was about 1000 megohms and there were about 100 relays paralleled, giving a total effective impedance around 10 megohms. This, in parallel with a 1-megohm input, introduced an appreciable error. This paralleled leakage error was minimized by dividing the relays used for analog signal selection into smaller groups and employing series relays to select each group.

Errors Caused by Intermodulation

Intermodulation was experienced when two sine waves of approximately the same frequency were closely coupled. A subsystem aboard a missile had its own internal oscillator designed for a center frequency of 400 cps. However, it was not specified to be frequency stable. Intermodulation was experienced between this oscillator signal when it was, for example, generating at 396 cps and the ground power unit at 400 cps, resulting in a 4-cps difference signal. The effect of this intermodulation was first noted when it was found that the Analog-to-

Digital Converter was varying at a four cps rate when measuring a steady state 400-cps a-c voltage. This four cps beat disappeared when a 400 cps vari-drive unit was substituted for the standard external 400 cps power unit and adjusted to 396 cps.

By employing a dual beam scope and d-c bucking voltage technique as previously described by R. J. Allen*, the low level four cps signal riding on the high level 400 cps signal was observed. Steps were taken to install special decoupling networks in this particular case to minimize this problem. The amount of error after installation of the networks was proportional to the amplitude of the four cps signal remaining.

Loop Analysis

The analysis of the various contributing factors in the loop was initiated after the functional block diagrams of each test stimuli and response loop were drawn and after the input and output impedances, cable losses, relay leakages, test tolerances and characteristics of the subsystem under test, and stimuli and measurement accuracies of the checkout equipment were determined.

A very small number of copper paths required coax cables or paralleling of conductor to minimize the signal degeneration. Conductors requiring shielding were determined and indicated. The study was completed by the determination of the checkout system's ability to perform the required functions with necessary accuracy determined at the interface point of the missile subsystem or launch control equipment. The ratio of the missile subsystem tolerance to the checkout system tolerances were calculated and ranged from a ratio of one, which is very poor, to over one hundred, which is greater than necessary. A ratio in the range of five to ten is considered satisfactory.

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* R. J. Allen, "Automatic Checkout System Errors", presented as part of a lecture series on Automatic Checkout for Aerospace Vehicles, UCLA, August 19-30, 1963.

SUMMARY

The detailed error analysis of an ICBM complex produced information on the effect of a distorted wave on measurement accuracy. It was found that "even order" harmonics, that are shifted in phase with relation to the fundamental, cause wave assymmetry that introduces an error when employing a peak detector; the amount of which depends upon which peak is being read. Odd harmonics and combinations of harmonics cause errors in the phase, synchronous, and/or peak detectors. These errors were minimized by using a unique zero phase shift, unity gain harmonic comb filter.

Large numbers of parallelled relays have combined open circuit leakages that must be considered when the checkout system input impedance is high. A missile subsystem with a local oscillator not frequency-locked to the central 400-cps power unit caused a low frequency beat that was sensed by the checkout system measurement section.

The study was completed after performing an integrated loop analysis of each functional test which indicated the need for special site cabling associated with a few analog signal functions.

TITLE: THE SYSTEM APPROACH TO AUTOMATIC CHECKOUT. PART I.

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Space Technology Laboratories, Inc.

History of Automatic Checkout

One way to open the subject of automatic checkout is to take a quick look at its history. Figure 1 shows some of the events or periods that in retrospect seem significant. My first recollection of anything automatic in test or checkout in electronics was in the early part of the War when I recall some automatic testers of small parts used in production. It's possible that the telephone company who had a lot of firsts, had automatic testing in their exchanges prior to that.

The first really significant built-in provisions for self test in a major system I recall was in a piece of Signal Corps equipment in about 1942—a small radar direction-finder whose scope was adapted for use as a test scope. That's not exactly automatic checkout, but it provides perspective. It was during the latter part of the War that vacuum tube digital computers came into use. As we'll see later, computers with proper input/output devices have a major capability in automatic checkout but after all this time their use for this purpose is still not extensive.

The first high speed successive approximation analog-to-digital converter appeared on the market about 1954 and it is one of the key developments that makes high speed digital checkout possible. The next line indicates what I think of as the era of special checkout equipment or units for various parts of large systems. That day has just about gone. Automatic sequences during testing and launching of rockets and engines appeared during about 1952 to 1955 and these evolved into today's sequentially-programmed card and tape machines. I show this era of sequential checkout with this bar starting in 1953. It's still with us, and I'm tempted to say, unfortunately. From 1956 to 1959 a major Air Force sponsored study of optimal automatic checkout for very large systems took place with several results. It was concluded that computer-like checkout equipment had capabilities beyond other types; that the prime system, however, had to be designed for testability, and that the objectives of test and checkout can and should be quantitative. Prime system and automatic checkout hardware was designed in detail but was never built.

The era of high speed digital data processors from the standpoint of hardware construction did get off to a slow start a year or two later. It has not been adopted as rapidly as it deserves—probably because system test requirements have not been fully defined and the applicability of a high speed data processor recognized. Last, I want to include some recent work—and there's a paper describing it—by Oyerly and King of ARINC, which is something of a milestone. This 1963 paper shows that there is an increase in equipment MTBF during operational periods as a result of checkout in greater depth. I'll cover these results in more detail later.

Well, if that's the history of automatic checkout, where do we stand today?

Current Status of Automatic Checkout

(Figure 2) It's safe to characterize the art of automatic checkout as unsettled. There's lots of literature but little continuity or cohesion. As a basis for comparison, and by way of contrast, the field of control systems and regulators is based upon a small number of related quantitative and physical principles. Such systems can be synthesized and optimized by well understood mathematical techniques which permit the synthesis and design of a system with confidence that the specified performance will be attained. This is not true today of automatic checkout generally. We at STL do think that it is true of our approach, although some of the detailed areas still require development and data. It involves the use of mixed strategies on a systematic basis. But in the field as a whole, there are no accepted principles, no complete, closed solutions, no accepted textbooks, nor systematic design techniques leading to complete designs. It is difficult to get agreement on optimal checkout equipment or checkout methods in specific cases. Everyone does seem to agree that more test and checkout provisions should be incorporated into the prime system design but today these provisions are frequently rudimentary and based entirely on end-to-end testing.

There are many varieties of card and tape programmed automatic checkout equipment used to check out today's large systems. Some effort has been made to standardize but with mixed success. Several organizations have done work in internally-programmed computer-like checkout devices. We feel strongly, as we will bring out, that this is an essential part of the ultimate solution to automatic checkout, but this conclusion requires considerable amplification and qualification, because work and results to date do not make the reasons obvious.

There has been considerable work recently in the development of mathematical techniques test point selection for automatic checkout and Mr. Coleman will talk about this later. So far, these cover very special cases on a selective basis and we think that probably test point selection and test methods themselves will always consist of a set of mixed strategies. We think a rationale can be developed to select from these objectively. Some of the assumptions that are often made in arriving at exact or probabilistic solutions also require closer scrutiny. They are often made on a mathematical or statistical basis, without regard to the circuit physics.

Checkout implementation still seems to be a seat-of-the-pants art with no stated objectives except to see that major system functions or end-outputs are currently within performance limits. There is, for example, no accepted measure of test efficiency. Our approach is based upon the support of mission reliability and system availability or in-commission rate on a quantitative basis as a top objective. The connection between test data numbers and the value of these gross system operational parameters is a little loose in some ways because of lack of data but I think we can show the general connection quite clearly.

The recent paper by Oyerly and King of ARINC that I mentioned before, proving among other things that actual operating MTBF of systems in the field is affected substantially by the quality of checkout independently of other factors such as inherent reliability, must be listed as a positive milestone in the art.

There are various other difficulties in synthesizing an acceptable automatic checkout rationale by culling the art as it stands today. Resolution of some of these requires definition of faults and failures. Generally, the literature is silent on this subject so I'm going to develop it a little later.

Another problem is the wide difference between the powerful test capabilities the art can easily provide, and the somewhat conventional but unevaluated test techniques and methods evolved from the past. Modern high-speed checkout equipment can extract status data from a system, the need for which has never been completely defined. It has never been defined for two reasons: because no rigorous and quantitative test efficiency measures and objectives have ever been identified, and because it has not been generally recognized that the means for extracting the data, applying the techniques, and processing the data are at hand.

In a nutshell, automatic checkout has considerable unrealized potential and much background, but is not a unified, settled science with accepted, quantitative methods.

Establishing the Maintenance Regime: Maintenance Functional Analysis

What do we mean by the system approach to automatic checkout? We mean two things; and this, and Figure 3 will help illustrate them. First we include all that has become an accepted analytical approach on our more sophisticated programs. This is sometimes called a maintenance functional analysis. The prime system is analyzed and such things as maintenance and repair flows and methods are established. From these, test equipment requirements fall out, together with personnel and skill level requirements and logistics data in the form of quantities of test equipments, handling equipment, and spare parts. These analyses get quite complicated in practice because of the number of factors involved and also use relative sophisticated techniques such as queuing theory to obtain solutions and computers to handle the data. But, in general, they deal only in tangibles such as man hours, down time, cost, square feet, performance time. They do not usually include depth of test, mission reliability, or test efficiency. There is some feedback into the prime system design, but this is usually for accessibility, disassembly, location of connectors, and so forth. We include or take for granted everything in this type of analysis in our system approach. We regard it as essential but we also add something. We see automatic checkout as assuming an important position in the system concept, because it has a major influence on overall system effectiveness parameters.

The Position of Automatic Checkout Equipment in System Maintenance Analysis

This diagram (Figure 4), in what is still an over-simplified way, shows some of these essential and new factors tying automatic checkout into the system approach.

First, we establish our top objectives. This will always include cost or system effectiveness which in turn usually includes probability-of-mission-success, and in-commission rate. Starting with these and the results of an analysis of the physical system we are able to establish such things as depth and frequency of tests, from which we can select test points and prepare fault isolation logic. These can be reduced to detailed tests and measurements with their proper limits, and eventually into machine language. The automatic checkout equipment requirements can be established and the equipment designed when the task is defined. But there are also several important feedback loops. It turns out that one of the test objectives is to wring fault or incipient failure data from the system. It also turns out that internally-programmed checkout equipment has an extremely powerful range of capabilities in making large number of measurements accurately at high speed and processing and cross-correlating the resulting data. We are not used to thinking about these capabilities and they do not come completely free but their availability must be taken into consideration in the system approach and in the tradeoff studies. These tradeoff studies are a key part of our approach and influence the entire maintenance regime. The automatic checkout end-products from all of this can be placed in three categories: (1) the design of the automatic checkout equipment; (2) the system design provisions (test points, instruments, etc.) for the kind of testing required; and, (3) the test program to connect the two. It appears to us that at the field checkout level, and assuming we convince you of the validity of our objectives, the outcome of this approach will generally be a decision to use computer-like, high-speed internally-programmed checkout equipment.

Mr. Peterson will discuss the reasons for this in terms of the capabilities of this equipment and some related details of the details of design-for-testability. Mr. Coleman will discuss some of the strategies in optimizing test point selection, fault isolation, and other quantitative techniques in the approach.

System (Cost) Effectiveness

(Figure 5) I'd like to turn now to the top objectives and sub-objectives of test and checkout and try to develop and clarify some of the concepts.

We build systems to perform some particular mission such as destroying a target. Once we have established a specific design to perform the particular mission, the system effectiveness is the mission reliability times the availability or in-commission rate. These measures are group, statistical or probabilistic parameters, but before we actually send a single system on a mission, (a priori), the group characteristic is the best way of estimating the chance of success of that system. As shown on this figure, system effectiveness would be the fraction of all systems purchased which would perform their mission. Some would be unavailable because of maintenance or for other reasons. Some would not get off the ground, a fraction would fail in flight, and another fraction might fly but just not hit the target even though they don't actually fail. With minor changes in the arithmetic, or just our viewpoint, we can equally well regard system effectiveness as cost per target destroyed, or targets destroyed per weapon expended, or the percentage of each program dollar spent, effectively, and so forth. The important point is that

these parameters are quantitative and after a system is operational they are a sufficient measure of system performance, so our basic objective is to see that they are maximized in our design and planning. Apparent availability is the fraction of all of the systems under consideration that appear to be ready for use by whatever standards of readiness we are applying. Mission reliability needs more discussion and definition.

Conditional Probabilities Comprising System Effectiveness

We've included on this Figure 6 the conceptually divisible factors which are a part of system effectiveness or mission-probability-of-success for some typical system separated in a way which brings out areas of interest in test and checkout considerations. Mr. Coleman will talk about some additional factors such as survivability and will also bring out the difference between apparent and actual availability.

If any one of these factors is less than one, 100% of the missions are not successful. The so-called "System Capability" block includes the cases where an adverse build-up of all of the uncontrolled tolerances and factors results in a lack of success. These include such things as mechanical and electrical tolerances perhaps combined with extreme environmental conditions or maximum performance requirements such as range. In any event, no actual equipment malfunction or human error occurs so this a statistic that is inherent in the design and the situation. Human error is another reason for failing to accomplish a mission.

The second block, "Equipment Reliability" is one of our principal areas of interest because it covers equipment faults and failures, because it is a large element in mission reliability, and because it is influenced by practically all phases of maintenance—especially checkout—as well as by the design.

This block of equipment failures is today generally the highest contributor to system unreliability, but it's important to note the fact that there are also other identifiable contributions. These provide a way of determining at which point it becomes uneconomical to devote further effort to reduce purely equipment faults or failures. In practice, we are far from this level of reliability.

Another important point is that availability is not really independent of equipment reliability. In fact, if there were no equipment faults, equipment reliability would be 100% and there would be no need for unscheduled maintenance although depending upon the system, preventive maintenance and servicing and just plain handling may cause down-time or unavailability.

But we are far from being in that situation, and equipment faults and failures result in equipment unreliability which is probably the larget single adverse factor in obtaining a 100% mission reliability. So our immediate objective in checkout is to reduce equipment faults either in the operational complex or during the mission to maximize both availability and total unreliability.

Before we leave this figure I want to relate what I'm calling equipment reliability to the inherent reliability of everyday engineering. My equipment reliability includes any and all equipment failures based upon a fabrication or design deficiency. It does not include abuse beyond normal wear and tear. That is human error in this context.

Inherent reliability generally means the reliability resulting from adding the published statistical failure rates of the parts and performing the necessary arithmetic. Specifically, my reliability includes a number of failure sources not usually included in inherent reliability and MTBF calculations which I'll come back to in a minute.

Tests and Test Data Flow in Various Stages of System Design and Use

A brief look at Figure 7 in passing will clarify what we mean by reducing faults by testing. Many tests are made during the development of a system from the first assembly to field operation. In each case design modifications can and usually do result as a result of the test data. In the later phases, particularly in field checkout where this presentation is centered, the action resulting from a test is usually a replacement or repair, although the design modifications never stop entirely. This long term and short term upgrading obviously affects the mission success.

One can get into a long argument over the question of whether a system test which results in no repair or replacement improves the mission reliability of that system. I prefer the simple view that it does, on an a priori basis and I will offer empirical evidence to support this later.

Some people compromise and agree that a parameter related to the risk or outlook which they call confidence, or confidence level, or commander's confidence is improved. I like these terms because the word confidence seems appropriate except for one thing. In statistics, confidence coefficient has a well-defined meaning. It means that a statement we make, which in engineering often contains a numerical value, will be true some specified high percentage of the time. In effect, it is a probability. But when we apply this classical concept to a reliability value we are basically saying that it is so-and-so probable that a probability is true. This is an unnecessarily complex way of getting to the point because physically there is only one question involved—what percentage of a group of systems will fail and what percentage will succeed?

In any event, we are here concerned with automatic checkout in the field and if there is any doubt about the reality or magnitude of the influence of test efficiency upon actual system MTBF, or reliability, I'll quote some recent empirical results a little later.

Failure Sources Not Included in Published Failure Rates

(Figure 8) I mentioned failure sources often not considered in statistical reliability. Here they are. I won't read them all but as you can see they can be organized into five classes. These are not rare or uncommon—the loose washer floating around in one of the Mercury capsule was a well-publicized example of a foreign object. These failures form too large a group to be ignored just because they're hard to evaluate.

The detection, prediction, and above all, the prevention of faults and failures are a primary objective of automatic checkout and I want to shore up some existing concepts and establish some new principles and definitions.

Basically, I am going to try to answer two questions:

What are failures and faults?
How do we detect, predict and prevent them?

In our everyday conversation, failure is a loose and subjective word. Literature I've seen also uses the word loosely without definition of what is meant.

Such phrases as random failure and catastrophic failures are hard to define objectively. Once we define failure I know what an unexpected or a sudden failure is, but I don't know exactly what a catastrophic failure or a random failure is.

We need language to facilitate everyday communication, but "failure" is used for too many different things for precise work and in a moment I'm going to define a fault. Usually, but not always, failure refers to the end-effect but not the cause. We probably should agree that failure means an overall visible effect involving a denial of some part of the system performance.

Failures Classified by Their Effects

(Figure 9) This figure shows failures defined and classified in this way—somewhat subjectively. A system failure means that we are unable to perform the primary mission. A mode failure means some part of it is denied to us. A limited failure means that we can perform the mission but poorly, and so on. A latent failure has no discernible effect upon an end-output and is in a class by itself.

In looking for ways to prevent these so-called failures we must go considerably deeper and ask why they occur. My answer is that they occur because of a singularity or abnormality which becomes a fault. Suppose a spacecraft transmitter stops transmitting data to the ground. It might be something wrong with the transmitter. But it also might be that the transmitter is not getting power from the power supply because the battery is dead. The battery might be dead because it is not being charged by the solar cells and the solar cells are not charging because they are not oriented toward the sun. This may be due to, say, an open resistor in the collector circuit of a transistor in the attitude control system. It is open because it cracked. We will get to why it cracked in a moment, but that crack is the basic fault. The resistor is the largest piece we must replace to restore operation, assuming the fault has not resulted in other faults.

This illustration is typical in two ways: it is not far-fetched. Faults in electronic systems frequently are felt in relatively indirect ways. Second, all equipment failures are based upon a physical and identifiable fault. But the reverse is not true: all faults do not cause failures nor are they even visible on system outputs.

But before we go into that let's examine briefly what we mean by a fault. A fault is a physical thing—it is always an abnormal configuration of material and this abnormal configuration is always measurable if we measure the right thing. In electronic circuits it is almost always measurable electrically, although in some cases it is not practical to do so.

We are used to the fact that measurements usually deviate from their central value. By and large these deviations are not faults. But, as we measure each parameter of each piece part there is a point where the deviation has to be considered abnormal because it already degrades performance, or, more likely, is indicative of a physical fault which will develop soon into what we customarily call a failure. In either case, we have to consider that the part has failed locally but this may have had little or no effect on the system nor even upon the output of the black box in which the part is located.

Definition of Equipment Failure

(Figure 10) On this figure we define equipment failure. It is subjective to the extent that it depends upon what we consider a useful end-output. It is the visible absence of all or part of some element of the useful end-output and is always based upon an internal fault, whatever the reason for the fault. An example is the spacecraft transmitter which stops transmitting.

Definition of a Fault/Abnormality

(Figure 11) A fault is a deviation in something physical and measurable which goes beyond normal limits. When a system design is proven and the system becomes successful as a type, we have an objective guide to normality and abnormality. If all of the measurable parameters of a particular system we are evaluating are within the same limits as those systems which have actually performed successfully under the same conditions, we can be certain we have a good one.

An example of a fault is a shorted cathode by-pass capacitor in a vacuum tube circuit. This is a fault or a local failure which probably does not cause an immediate equipment or system failure.

Now, I want to make the point that all equipment failures are theoretically predictable. They are predictable because they are based upon faults which in turn are physical. Physical conditions are measurable and predictable because each physical state of the universe, or any part of it, follows from the preceding state. With some possible exceptions in particle physics which don't apply here, there is no such thing as chance in nature. To bring this into our sphere of interest, if one resistor in a thousand fails while the other 999 do not—under identical conditions—then there was something physically different in that resistor however it may have got there. If we had looked closely enough we could have predicted the failure or fault and weeded it out. Faults like any other collection of facts can be described statistically but individually they are physical facts and are not inevitable. They must be identified and prevented on this basis.

Mr. Coleman and Mr. Peterson will shed light on how to do this, and I will provide some facts to demonstrate that this is not only theoretical but is also practical.

Conditions Preventing Faults from Affecting "Outputs"

(Figure 12) I want to digress for a moment and make a point that seems to need discussion. Faults are usually not visible on end-outputs or even sub-outputs in their early or even their advanced stages. Sooner or later they become a failure and then they are. There are thousands of examples, but the principal reasons for this are on this figure with one example for each.

Electronic circuits have many indirect or secondary functions such as power supply, biasing, etc. Faults or even complete parts breakdowns often do not manifest themselves immediately although they are locally measurable. An example is the shorted by-pass capacitor in the cathode of a vacuum tube. This applies improper bias to the grid of the tube but the tube may go on working for quite a while.

All parts of an electronic circuit contribute in some way, but the output is often not sensitive to changes in parameter values well outside the normal range.

An example is a plate load resistor. These may be five per cent resistors but many circuits are tolerant of 20% or even 50% deviations.

Overloads. I have seen many power transformers overheated by internally shorted turns that are still providing normal gross performance even though they are nearly in flames.

A redundant part may fail but its twin will continue to perform the function for a while, so the local failure has no effect.

Last but far from least is a very large class. Many of today's systems contain large closed loop control systems. It is a characteristic of negative feedback, in fact its purpose—that it forces the output to equal the input over a wide range of conditions by a process of error detection and compensation.

These conditions include wide deviations in the internal parts even those in the main channel. I have seen gain stages so far gone they supply essentially unity gain but the control system is still working.

In leaving this subject I want to point out that while these faults or local failures—whatever the semantics—cannot be distinguished from normal deviations in some end-output, they can usually be measured locally as in my examples.

I've defined faults and failures for convenience and now I want to indicate as specifically as possible what they are.

Failures Classified by Physical Manifestations

(Figure 13) To list all possible fault or failure modes and mechanisms for every part or assembly would be impossible but they fall into classes. This figure shows these classes and the kinds of faults that comprise them. All faults as I have defined them fall into one of these physical categories. They may involve a configuration abnormality such as a break or crack, a loose part, presence of foreign matter and so forth. Or, they may involve with less likelihood, a composition abnormality such as excessive impurities or a degradation such as corrosion. The fault may be associated with an entire assembly rather than with any single part. Oscillation or instability is an example of this. But their source is always physically identifiable.

Failures Classified by Causes

(Figure 14) Equipment faults do not usually occur suddenly, although their development into what we are calling a system failure may be sudden. We can see this by considering the generalized causes of faults and failures on this figure. Fault causes fall into three categories: an abnormality introduced at some stage of fabrication, a misapplication of the particular element, or some abuse.

All fabrication abnormalities are potentially detectable at any time since they are continuously present. Many are such small flaws that even at part level they can't be resolved until after they have been developed somewhat by operational stresses.

A misapplied part is one subjected to the wrong electrical or physical environment or from which the correct output is not obtainable. These cases should be detected in some test before the equipment reaches the field, but if they are not, they can be detected by automatic checkout in the field in several ways.

Faults resulting from abuse can happen suddenly, if the abuse function is applied suddenly and excessively. If the abuse is characterized by a slow degradation in some local parameter, including such parameters as temperature and vibration, faults in this category can be detected before they develop into a failure and the failure prevented. But many of these faults and failures fall into the operational human error category and cannot be predicted or prevented by automatic checkout.

I think I can put what I have said about faults and failures into simple, concise language. Total system or mode failures, especially during a mission, is what we are interested in. These are all caused by physical faults many of which are built in. These will not, in general, first be visible on some end-output, but nevertheless can theoretically be detected before they become a full system failure.

Mr. Coleman and Mr. Peterson are going to talk about <u>how</u> this can be done.

I want to convince you now that it is really practical to <u>do</u> it and that we do get the predicted results.

Oyerly & King (ARINC) Results

(Figure 15) A well controlled experiment comparing the results in terms of operational MTBF or reliability of a thorough test and overhaul versus conventional techniques was conducted by ARINC personnel at the Dayton Air Force Depot. The results show clearly the effect of test efficiency upon mission reliability and demonstrate the mechanics by which the results are obtained. In this experiment a large sample of airborne communication set was maintained by two different methods and the subsequent performance in the aircraft was recorded. This was a mature equipment and the conventional maintenance procedures were well established. The equipment was of subsystem or large black box size containing 55 tubes, and 1561 electronic piece-parts. The non-conventional test techniques were characterized more by their comprehensiveness than by their automaticity although semi-automatic checkout equipment was used to perform them. It was necessary to completely disassemble the equipments to perform these tests in order to provide the required detailed access. Tubes were removed and checked on a semi-automatic tester. The tests were to the sub-assembly and piece-part level. Overall tests were also performed before and after disassembly. The conventional overhaul also involved good overall passive and dynamic performance tests but not the tests at parts and sub-assembly level.

This figure tabulates a few of the results. The actual operational MTBF of the comprehensively tested group was 37 per cent higher than the group which was conventionally maintained. In other words, the operational reliability of the entire group was substantially increased by a thorough test. The reason for this lies in the number of parts replaced. 2190 parts were weeded out of the specially tested units while only 328 in those conventionally checked. But still those conventionally checked had passed their fairly complete overall tests before they were installed in the aircraft.

Other results demonstrate the reality of the point I made earlier; namely, that a unit which is tested throughly and passes the test without repair is statistically more reliable than one which passes a more cursory test or no test at all. Equipments removed from aircraft for maintenance during the test were not always found defective, and records were kept of the subsequent performance of these units which were tested but in which no actual changes were made. Those which were verified by the thorough test were 83 per cent successful on the next flight, but those which passed the standard tests were only 70 per cent successful the next time out.

The average cost of manual field maintenance per thousand hours of operation was $174 for the units which had been thoroughly checked at the depot versus $334 for those conventionally overhauled.

Nine hours and 52 minutes were required for the comprehensive test which included disassembly and some 2000 tests and reassembly compared to three hours and 40 minutes for the conventional overhaul tests. So, this is one reason why I think this is better referred to as a comprehensive test rather than an automatic one. Nevertheless, the comprehensive tests cost only $151 compared to $137 for the conventional tests, so it was still cheap.

Mr. Oyerly and Mr. King are to be congratulated for their paper (Reference 1) whose results I've been quoting and their part in the work. The organization and conduct of this experiment make the validity of the results beyond question.

One may ask now whether in view of the substantial improvements achieved by what I have described as partly semi-automatic and partly manual tests, the use of a sophisticated computer-like checkout equipment can be justified. The answer is "yes", for several reasons. It would not be possible to remove and dismantle the subsystems of an aerospace system on the pad in this way. This procedure itself introduces new incipient failures. It is not feasible to secure the necessary data without the design-for-testability process and test provisions Mr. Peterson is going to discuss, nor to make the measurements or perform the data processing and reduction without the faster, and more sophisticated equipment. Last, some of the methods which will be associated with the internally-programmed automatic checkout equipment are very sensitive to fault detection, and if these design-for-testability methods had been applied to the communication set under consideration when it was designed I have no doubt that still further substantial increases in operational reliability would be experienced.

With this background and empirical results I hope I've set the stage adequately for the next two parts of this paper by Mr. Coleman and Mr. Peterson.

REFERENCE

(1) Oyerly, Philip R. and King, Dewey C., "A Controlled Study of Automated Testing Techniques," Proceedings, Ninth National Symposium on Reliability and Quality Control, San Francisco, Calif., January 22, 23, 24, 1963.

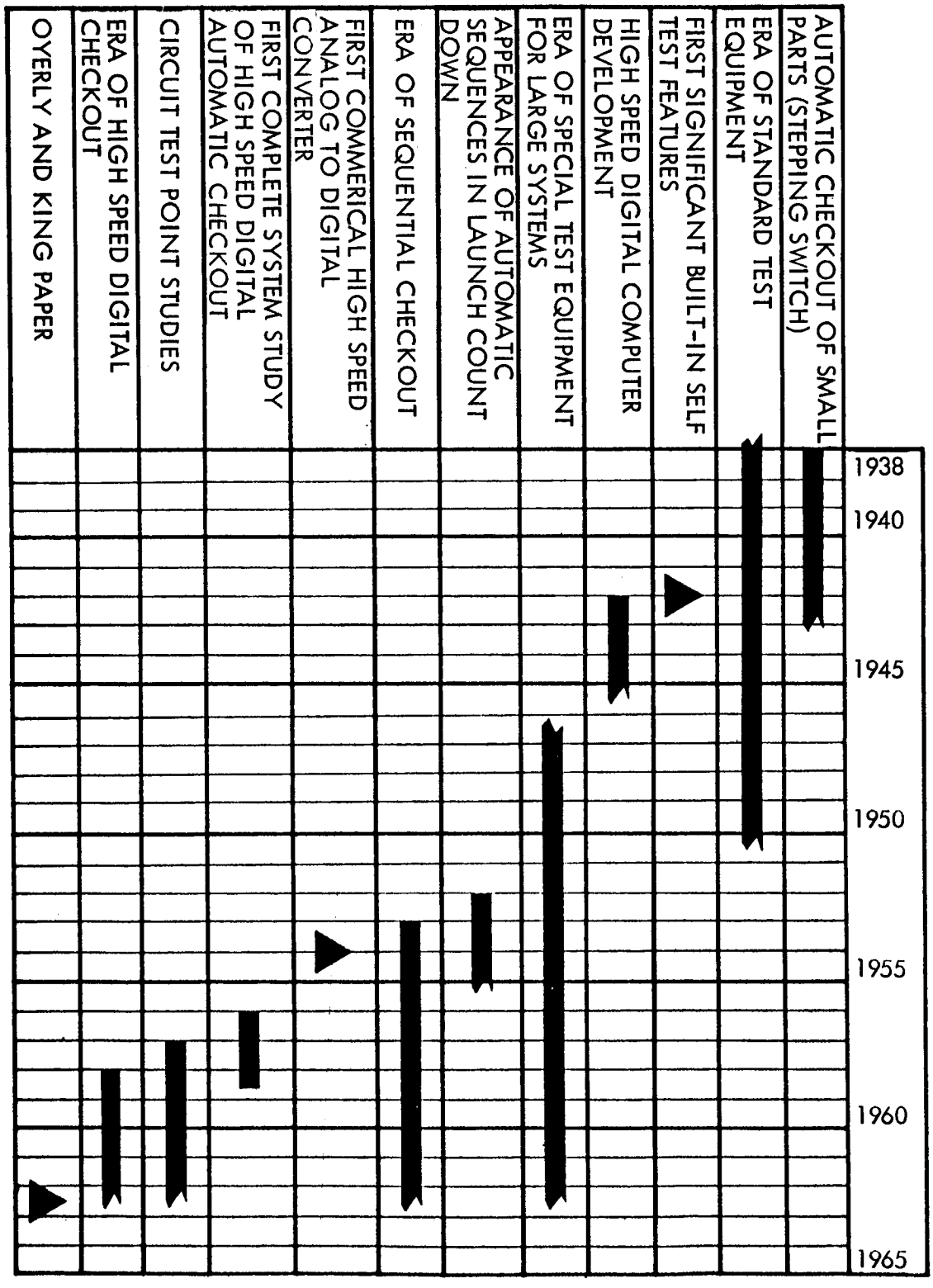

Figure 1. History of Automatic Checkout

CURRENT STATUS OF AUTOMATIC CHECKOUT

1. Automatic Checkout Is Not Unified
    a. No accepted principle
    b. No complete closed solutions
    c. No accented textbooks
    d. Not mated with System Design

2. Heterogeneous Equipment
    a. Card programmed
    b. Tape programmed
    c. Internally programmed

3. Mathematical Techniques for Test Point Selection
    a. Cover special cases
    b. Physical assumptions require scrutiny

4. ACO Objectives
    a. Reliability/Availability
    b. Arinc/Dayton AFB experiment shows effect on MTBF

5. Difficulties in Rationale
    a. Definition of faults and failures
    b. Test requirements vs. test capabilities

Figure 2.

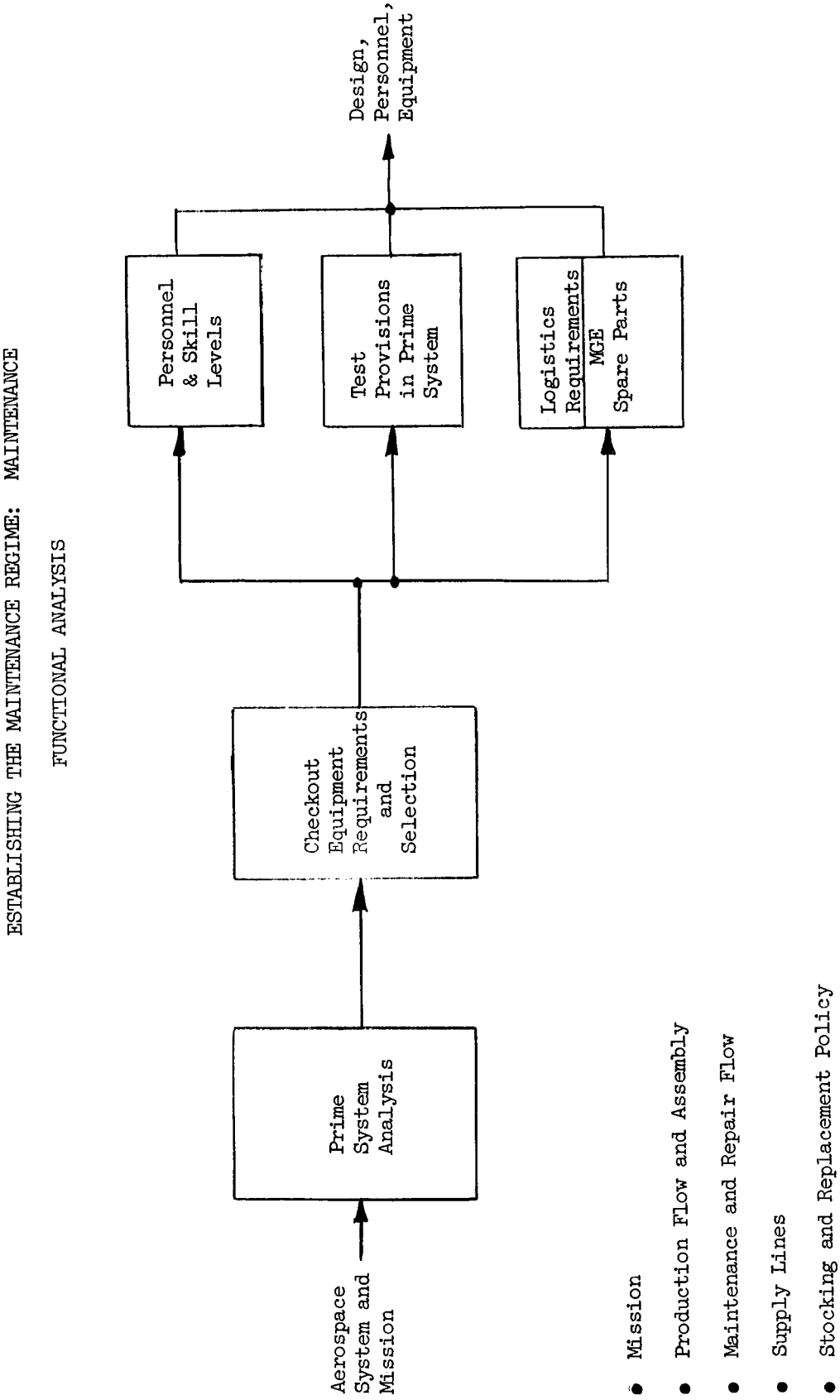
ESTABLISHING THE MAINTENANCE REGIME: MAINTENANCE
FUNCTIONAL ANALYSIS
Aerospace System and Mission
Prime System Analysis
Checkout Equipment Requirements and Selection
Personnel & Skill Levels
Test Provisions in Prime System
Logistics Requirements
MGE
Spare Parts
Design, Personnel, Equipment
• Mission
• Production Flow and Assembly
• Maintenance and Repair Flow
• Supply Lines
• Stocking and Replacement Policy

Figure 3.

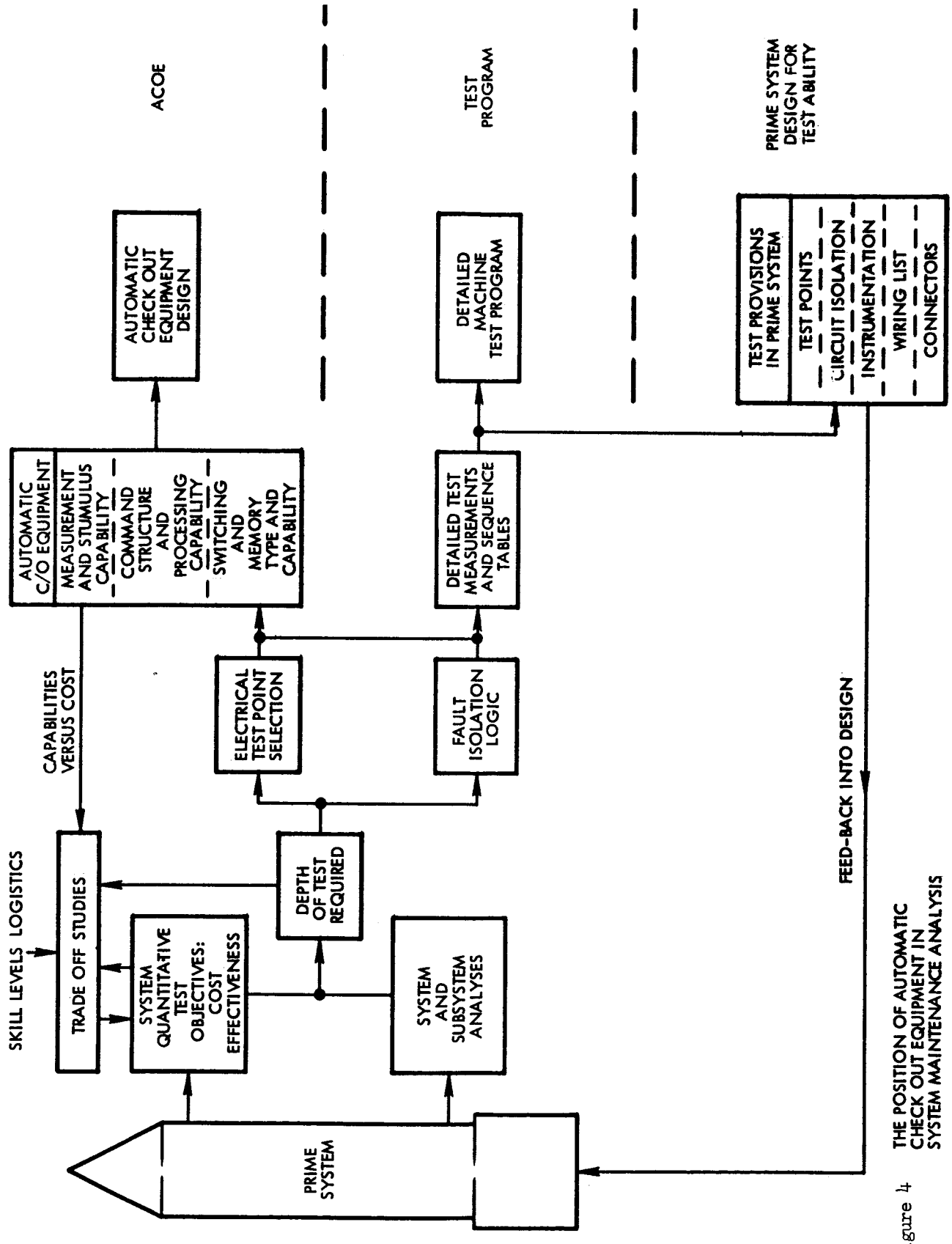
ACOE
TEST PROGRAM
PRIME SYSTEM DESIGN FOR TEST ABILITY
AUTOMATIC C/O EQUIPMENT
MEASUREMENT AND STUMULUS CAPABILITY
COMMAND STRUCTURE AND PROCESSING CAPABILITY
SWITCHING AND MEMORY TYPE AND CAPABILITY
AUTOMATIC CHECK OUT EQUIPMENT DESIGN
DETAILED MACHINE TEST PROGRAM
TEST PROVISIONS IN PRIME SYSTEM
TEST POINTS
CIRCUIT ISOLATION
INSTRUMENTATION
WIRING LIST
CONNECTORS
DETAILED TEST MEASUREMENTS AND SEQUENCE TABLES
ELECTRICAL TEST POINT SELECTION
FAULT ISOLATION LOGIC
CAPABILITIES VERSUS COST
SKILL LEVELS LOGISTICS
TRADE OFF STUDIES
DEPTH OF TEST REQUIRED
SYSTEM QUANTITATIVE TEST OBJECTIVES: COST EFFECTIVENESS
SYSTEM AND SUBSYSTEM ANALYSES
PRIME SYSTEM
FEED-BACK INTO DESIGN
THE POSITION OF AUTOMATIC CHECK OUT EQUIPMENT IN SYSTEM MAINTENANCE ANALYSIS
Figure 4

Figure 4.

GROSS OR AVERAGE SYSTEM EFFECTIVENESS

$$\text{SYSTEM (COST) EFFECTIVENESS} = \text{MISSION RELIABILITY} \times \text{AVAILABILITY}$$

$$\frac{(\text{Successful Systems})}{(\text{Systems Purchased})} = \frac{(\text{Successful Missions})}{(\text{Missions Attempted})} \times \frac{(\text{Systems on Line})}{(\text{Systems Purchased})}$$

Figure 5.

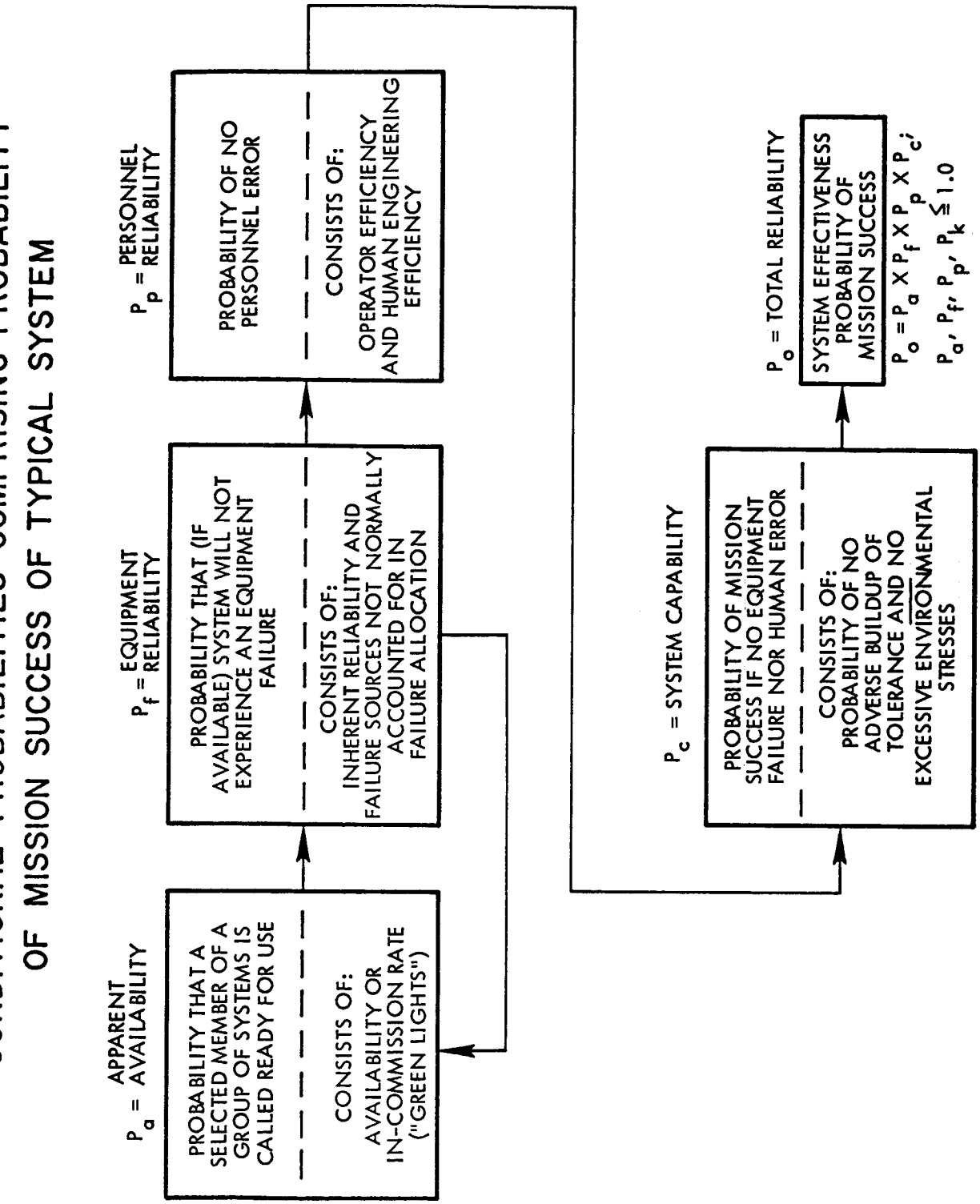

Figure 6

Figure 6.

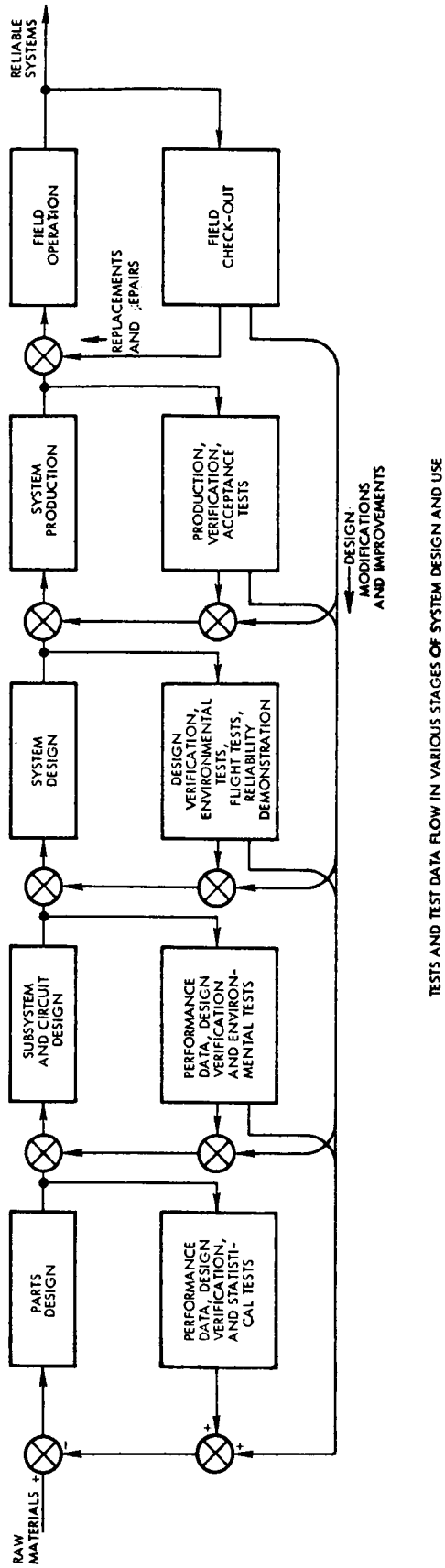

Figure 7.

Figure 7

FAILURE SOURCES NOT INCLUDED IN PUBLISHED FAILURE RATES

1. FOREIGN OBJECTS

   a. Loose conducting material
   b. Trash and dirt
   c. Support and service equipment
   d. Improper assembly-extra parts

2. MECHANIAL FAILURES

   a. Loose parts
   b. Bent parts
   c. Displaced wiring
   d. Abraded wiring
   e. Corrosion
   f. Broken parts
   g. Omitted parts - improper assembly

3. ELECTRICAL FAILURE NOT ATTRIBUTED TO A SINGLE PART

   a. Instability and oscillation
   b. Noise or RFI pick-up
   c. Interface problems
   d. Common mode voltages

4. ERRORS

   a. Error in reading tape
   b. False counts

5. AGED EQUIPMENT

   a. Secondary damage
   b. Overloads - overstress
   c. Excessive service life

Figure 8.

FAILURES CLASSIFIED BY THEIR EFFECTS

Failure	Overt Effect
• System Failure	Primary mission fails
• Mode Failure	Part of the mission fails
• Limited Failure	Degraded performance
• Latent Failure	Cannot be resolved
• Progressive Failure	Full effect delayed
• Volatile Failure	No permanent damage

Figure 9.

DEFINITION OF EQUIPMENT FAILURE

Failure:

An equipment failure is the visible absence or abnormal degradation of an element of equipment useful end-performance due to an internal fault or faults.

Examples:

A spacecraft transmitter stops transmitting.
An engine fails to start or command.
A missile falls short of the target.

Figure 10.

DEFINITION OF A FAULT/ABNORMALITY

Fault:

An abnormal physical state of equipment which causes an equipment failure or poses an unacceptable threat to an end output. An abnormality is the deviation of some measurable parameter or characteristic beyond those limits estimated by the designer (immature equipment) or found by experience (mature equipment) to be normal to similar successful equipment.

Examples:

A shorted cathode by-pass capacitor.
A cracked resistor.
A piece of solder causing a high resistance short.

Figure 11.

CONDITIONS PREVENTING FAULTS FROM AFFECTING "OUTPUTS"

1. Secondary Function

   Example: Shorted cathode by-pass capacitor

2. Circuit Insensitivity to Parameter Value

   Example: Cracked plate load resistor

3. Tolerance of Temporary Overloads

   Example: Shorted turns in power transformer

4. Redundancy

   Example: Contacts in parallel

5. Control Loops - Regulators - Feedback Circuits

   Example: Bad amplifier (low gain) not detectable

Figure 12.

FAILURES CLASSIFIED BY PHYSICAL MANIFESTATIONS

CONFIGURATION ABNORMALITIES

1. Breaks and cracks
2. Distortion and warpage
3. Abnormal size or shape
4. Presence of foreign matter
5. An omission
6. Depletion, wear, and abrasion
7. Change in gain structure
8. Mechanical and electrical misadjustments - loose parts - improper positions

COMPOSITION ABNORMALITIES

1. Wrong material
2. Excessive impurities
3. Change in composition
4. Degradation - corrosion

Figure 13.

FAILURES CLASSIFIED BY CAUSES

FABRICATION ABNORMALITIES

- Can be any one of the 12 - failure manifestations

MISAPPLICATIONS

- Element unsuited to normal operating conditions
- Element not designed for normal environment
- Element not designed for combined operational stresses
- Combination of reduced performance of several elements: marginal design

ABUSE

- The actual operating conditions exceed those stipulated
- The actual environment is more severe than that stipulated
- Mis-adjustments
- Operating errors: faulty loading, servicing, rigging or stowing

Figure 14.

OYERLY & KING (ARINC) RESULTS

Equipment: Airborne Communications Set

Electronic "Size": 55 tubes; 1561 parts

Sample Size: 140 (70/70)

- MTBF Increase from Comprehensive Test: 37%
- Parts Replaced after Comprehensive Tests: 2190
- Parts Replaced after Standard Overhaul Tests: 328
- First Flight Reliability of "Non-Defective" Units:

  Comprehensive Test: 83%
  Standard Overhaul Test: 70%

- Field Maintenance Costs per 1000 hours:

  Comprehensive Test: $174
  Standard Overhaul Test: $334

- Cost and Time of Tests:

  Comprehensive Test: $151/9 hrs., 52 min.
  Standard Overhaul Test: $137/3 hrs., 40 min.

Figure 15.

THE SYSTEMS APPROACH TO AUTOMATIC CHECKOUT (PART II)

by
John J. Coleman

I INTRODUCTION

The control of the operational status of aerospace systems is of paramount importance to both our military and our civilian aerospace programs. To establish and maintain the operational effectiveness of an aerospace system, it is necessary to determine and evaluate its status in order to select and execute maintenance actions which will, in turn, maintain or improve the operational capability of the system. Consequently, readiness testing and replacement-repair actions are necessary, even though test severity, errors, frequency, duration, and coverage, as well as repair durations and uncertainties, all influence the probability that the system will be ready for use when demanded.

The concept of rapid testing of a complex set of interrelated functions to measure overall system status usually leads to the consideration of high-speed, automatic, computer-type checkout equipment. Generally, automatic checkout equipment (ACE) has been and will be used to accomplish tasks beyond human capability or to realize greater efficiency.

The basic objective in the design of ACE is to insure a high degree of system readiness or availability. In implementing this objective, the prime system must be designed to permit adequate testing, the ACE must be designed to provide adequate testing, and the two must be interrelated by quantitative system models which provide better standards and parametric tradeoffs for the preliminary design of present and future aerospace systems.

In order to approach the checkout problem properly, the entire aerospace system must be considered. The objectives or goals for the system should be defined as precisely as possible. Operational assessment criteria must then be established which reflect these objectives adequately.

Then, the functions necessary to accomplish these objectives must be established and related to the assessment criteria, in order to provide the proper tradeoffs needed for overall system optimization.

Of major influence on the final system configuration are the operations and maintenance plans. These plans are clearly associated with the checkout hardware functions at all levels. Equipment functions, such as automatic checkout, must be considered in terms of their operations and their effects on maintainability, reliability, etc., during these operations. The sampling, comparison, and interpretation of status information by automatic checkout equipment must be analyzed and integrated by the systems approach, in order to provide the proper type and level of automation needed for optimizing overall system status control.

II OPERATIONAL ASSESSMENT CRITERIA

In considering the value of aerospace systems, management is interested in knowing how a given system compares with other systems (relative effectiveness in performing specified missions). On the other hand, management might be more concerned with how many of each system would be the optimum combination than with which particular system is best. Nevertheless, before optimum mixes of aerospace systems can be decided, criteria must be chosen to compare the operational effectiveness of each type of system and methods for evaluating these criteria must be established.

In making a quantitative comparison of each type of aerospace system, the following set of assessment criteria must be considered:

Command Control Success Probability, S_c, i.e., the probability that the command control system properly exercises all policy relative to authorizing and authenticating orders to launch, as well as all policy relative to preventing an unauthorized or unauthenticated launch. Obviously, the command control area is intimately connected with status control functions at all levels of operation, and also reflects communications, targeting, and the objectives which the particular aerospace system is required to accomplish (hopefully the same as those for which the system was designed). In the case of a military system, this probability would also include the survival probability of the command-control system.

Survivability, S_b, which in case the system is a military one, is the probability of survival of the weapon system during its basing mode from enemy overt or covert actions.

Operational Readiness, O, i.e., the probability that the system will be operative and ready for use within a given set of demand times, random or scheduled. The demand times may be unknown, as in the case of a "surprise" situation, or the demand times may be scheduled, as in the case of programmed situations.

A surprise demand, for example, might be an emergency, like an in-flight abort or a response to a surprise attack. If the emergency time is completely uncertain, the long run proportion of time the system is ready for use might be the pacing factor. However, the delay readiness, i.e., the probability that the system can be made ready in time to be useful, should also be included in the overall readiness probability. But the time required to respond to emergency situations might be relatively short. In contrast, scheduled demands might be a continuous or a discrete set of time intervals, programmed and known in advance, within which the system must be started on to the next phase. The sequence of times required to complete the transition could be relatively long. Operational readiness includes, then, the probability of successfully starting the system on to the next state during the total demand period.

Although operational readiness might be thought of here in terms of launch readiness, this probability also includes the readiness of systems during any phase of the total mission, including starting transitions to subsequent nominal phases as well as changing or redirecting the mission, and emergency aborts.

Delivery Reliability, R, i.e., the probability that the activated system unit(s) will be successfully delivered to the destinated area(s), intermittent or terminal. This includes the entire sequence of operational transitions necessary to complete the overall mission.

Penetrability, P, which in the case of a military system, is the probability of the delivered unit(s) penetrating the enemy defense system or surviving enemy countermeasures which attempt to destroy the effect of a vehicle launch.

Payload Success Probability, D, i.e., the probability that the delivered payload will provide the final payoff intended. For example, in the manned lunar mission, the crew is a part of the payload, which also includes life support equipment, etc. In this case, the payload success

probability might be the probability that the crew survived the lunar flight. For thermonuclear warheads, the payload success probability would be the target kill probability.

Costs, C, i.e., the initial investment and costs of deployment and operation.

In planning and/or evaluating an aerospace system intended to perform a given mission, it is imperative that a study be performed to determine the system configuration and methods of employment and deployment which yield the most effective system in terms of all seven of the above factors.

A rudimentary analysis may simply multiply the first six factors together and divide by the cost. Alternative analyses, however, might consider the costs involved for a given probability of payload success. For example, in the case of single warhead payloads attacking point targets, the combined target kill capability K for m payloads is given by:

$$K = 1 - \left[1 - S_c S_s \, ORPK_1 \right]^m \qquad (1)$$

where K_1 is the single-shot kill probability. If a given level of kill is chosen, e.g., K = 0.90 for a given target or family of similar targets, then Equation (1) can be solved for m, the number of weapons required. Combining this with the cost per weapon, one may obtain the cost for any given kill level.

Similarly, for a manned lunar mission, the probability of at least one success out of m programmed flights might be expressed by:

$$P(I) = 1 - \left[1 - S_c ORD \right]^m \qquad (2)$$

In this case, however, m would obviously be greater than the number of vehicles required, since not all programmed launch attempts might be successful, and the same vehicle(s) could essentially be rescheduled, providing design adequacy exists.

While the composition of the system effectiveness criteria is rather simple, each criteria is functionally dependent upon the behavior of more specific characteristics. Specific relationships must be determined to evaluate the relative influences of the component variables and to establish methods by which these influences might be modified. Reliability and maintainability, for example, must be evaluated in terms of overall system effectiveness. Otherwise, the proper design and control of the operational capability would involve a confusing collection of interrelated factors and parameters.

Evaluation of reliability and maintainability requirements through the use of quantitative system models should provide better standards and parametric tradeoffs for achieving the best operational capability of present and future systems. It is desirable to consider all the interactions, such as performance estimation, weight scaling laws for trading-off on-board maintenance equipment, spares, test point selection, and failure prediction.

The question as to whether the system or the model should come first depends upon how much one might restrict the development of the other. In general, the model and the design should interact, Furthermore, the generalized model should consist of various subprograms, each of which is allowed to interact with the others and to become updated as well as adaptive as required. Such models should have the seed of adaptability for mission optimization. By proper development and implementation of these models, they can be applied directly to the design and evaluation of checkout equipment and procedures for any complex system performing a given mission, subject to all constraints such as costs, schedules, and human safety.

III ILLUSTRATIVE SIMPLE MODELS

Consider, for the sake of example, from Equation (2), the probability ORD of launching a payload from earth within a sequence of k launch windows of duration W. Note that even if the given launch attempt fails to occur within the prescribed mission period of k windows, the vehicle is still available for future mission periods. Corresponding to Equation (2), we will consider the probability, P (1), of at least one successful flight over m mission periods, each having exactly k allowable launch windows. Allow these windows to reoccur periodically where T represents the lapse time from the end of a given window to the beginning of the next.

Assume the detection of failures to be a continuous phenomena and the failure and repair distribution to be exponential. Now, let the probability of being ready at the beginning of the first window be denoted by p_u. Then the probability of launching within the first window is given by:

$$p_u + (1 - p_u) \left[1 - p_f(W)\right] \tag{3},$$

where $p_f(W)$ represents the probability of not being repaired within W, which is given by:

$$p_f(W) = e^{-\mu W} \tag{4},$$

Then if no success occurs within the first window, the probability of failing to start launch within any given remaining window is given by:

$$p_{ff}(T)\, p_f(W) \tag{5},$$

where $p_{ff}(T)$ represents the probability of being in a failed state at the start of a launch window, given that the system was in a failed state at the end of the previous window.

An expression for $p_{ff}(T)$ can be found from the above assumptions of exponential distributions, regarding the detection of failures to be a continuous process. Then, the probability of being failed, $p_f(t)$ at time t, is given by the difference equation:

$$p_f(t+\Delta t) = p_f(t)\left[1 - \mu\Delta t\right] + \left[1 - p_f(t)\right]\lambda\Delta t \tag{6}$$

where μ and λ represent the mean repair rate and failure rate, respectively.

In the limit as $\Delta t \to 0$, we obtain from Equation (6) the differential equation:

$$\lim_{\Delta t \to 0} \frac{p_f(t+\Delta t) - p_f(t)}{\Delta t} = \frac{dp_f(t)}{dt} = -(\mu + \lambda)\, p_f(t) + \lambda \tag{7}$$

which for the boundary condition of $p_f(0) = 1$, yields the solution

$$p_{ff}(T) = \frac{\lambda + e^{-(\lambda+\mu)T}}{\lambda + \mu} \tag{8}$$

Then the probability, ORD, of a successful launch within the k windows is given by:

$$ORD = p_u RD + (1 - p_u)RD\left\{1 - \left[\frac{\lambda + \mu e^{-(\lambda+\mu)T}}{\lambda + \mu}\right]^{k-1} e^{-k\mu W}\right\} \tag{9},$$

and assuming $S_c = 1$ in Equation (2), the probability of at least one success out of m mission periods is given by:

$$P(\underline{1}) = 1 - \left[1 - ORD\right]^m \tag{10}$$

where ORD is given by Equation (9).

We note that the operational readiness probability 0 in Equation (9) includes both immediate readiness as well as delayed readiness terms, corresponding to programmed demand situations, were p_u corresponds to the probability of being placed in readiness condition at the time of the first programmed launch window, as distinguished from being ready at some unknown random demand time, as in the case of systems that must be ready for an alert situation.

After a given assembly and prelaunch preparation time, then the system would be maintained in a high degree of readiness until used. If the interval from the time the system is first ready until the time it is first demanded is indicated by the time interval τ, then employing Equation (7) for the boundary condition $p_f(0) = 0$, then p_u will be given by

$$p_u(\tau) = 1 - p_f(\tau) = \frac{\mu + \lambda e^{-(\lambda + \mu)\tau}}{\mu + \lambda} \tag{11}$$

In the case of random demand situations, where the demand time will be equally likely to occur anywhere in a time interval L, then the immediate operational readiness will be equal to the long run proportion of time ready, or

$$p_u = \lim_{L \to \infty} \frac{1}{L} \int_0^L p_u(\tau) d\tau = \frac{\mu}{\mu + \lambda} \tag{12}$$

Since there would probably be only one window, then the operational readiness 0 of alert systems would be given by:

$$0 = \frac{\mu}{\mu + \lambda} + \frac{\lambda}{\mu + \lambda} \left[1 - e^{-\mu W} \right] \tag{13},$$

in the case where the system is completely, continuously monitored with no uncertainties or imperfections in checkout or repair.

If the systems are periodically checked, then the proportion of time that the system will be immediately available for use, assuming perfect maintenance, is given by: (reference 1)

$$P_u = \frac{1 - e^{-\lambda T}}{\lambda(T+T_c) + \lambda T_p \left[1 - (1-q)e^{-\lambda T}\right]} \qquad (14)$$

where λ now represents the standby failure rate

T represents the standby time between checks

T_c represents the mean duration of the checkout time

T_p represents the mean duration of the malfunction isolation plus replacement time

and q represents the probability of failure during checkout.

These relatively simple readiness models just described do not incorporate the more realistic effects of test and repair uncertainties. To visualize these more detailed but equally important characteristics, a further breakdown of the elements of the operational status control process is necessary.

For such realistic models, we must include the effects of:

- Imperfect repair
- Incomplete test coverage
- Failures of inherently undetectable characteristics

and

- Errors in calling a system good when it is bad; or calling it bad when it is good.

Of course, the models also must include the effects of the more easily obtainable parameters, such as:

- Operating time
- Down time
- Repair time
- Detectable failure rates

and

- Repair rates

IV ELEMENTS OF OPERATIONAL STATUS CONTROL

The typical elements of operational status control and their interrelationships are illustrated in Figure 1. Status control might be defined[2] as the actions and decisions that are required to achieve the desired operational capability of the system or equipment. Consequently, status control involves determining the system status and the decisions and actions at both system and lower levels, including both operational and maintenance control. The concept of rapid testing of a complex system to measure its status generally leads to the consideration of high-speed, computer-type checkout equipment. Breaking down the actions and decisions involved in operational status control enables an overall assessment of the interactions of reliability, maintainability, checkout, spares provisioning, etc. For Figure 1, a brief description of the basic elements are given below:

Reliability Factors. Reliability factors include descriptions of the modes of failure, how design specifications are related to failure definitions, tolerance limits, etc. In the previous part of this integrated paper, Kirkman classified and defined failures. Certain attributes of each system element which characterize its reliability performance were identified. These attributes may or may not be measurable in practice without distrubing the element in some way. The implication, should be, however, that more testing might be desirable to be able to measure the harbingers of failure.

Test Coverage. Considering each subsystem as a replaceable module, then each subsystem contains a group of functions, or devices, in which processes can take place. In general, then, each subsystem has several inputs and several outputs and a number of functional relationships or transfer functions between them, this number corresponding to the number of relatively independent functions. Now, not all functions or devices, in which processes can take place, can be directly tested, due to testability limitations, irrevocable processes, etc. In some of these cases, indirect tests can be made, such as x-rays on a solid rocket; even indirect tests, however, cannot

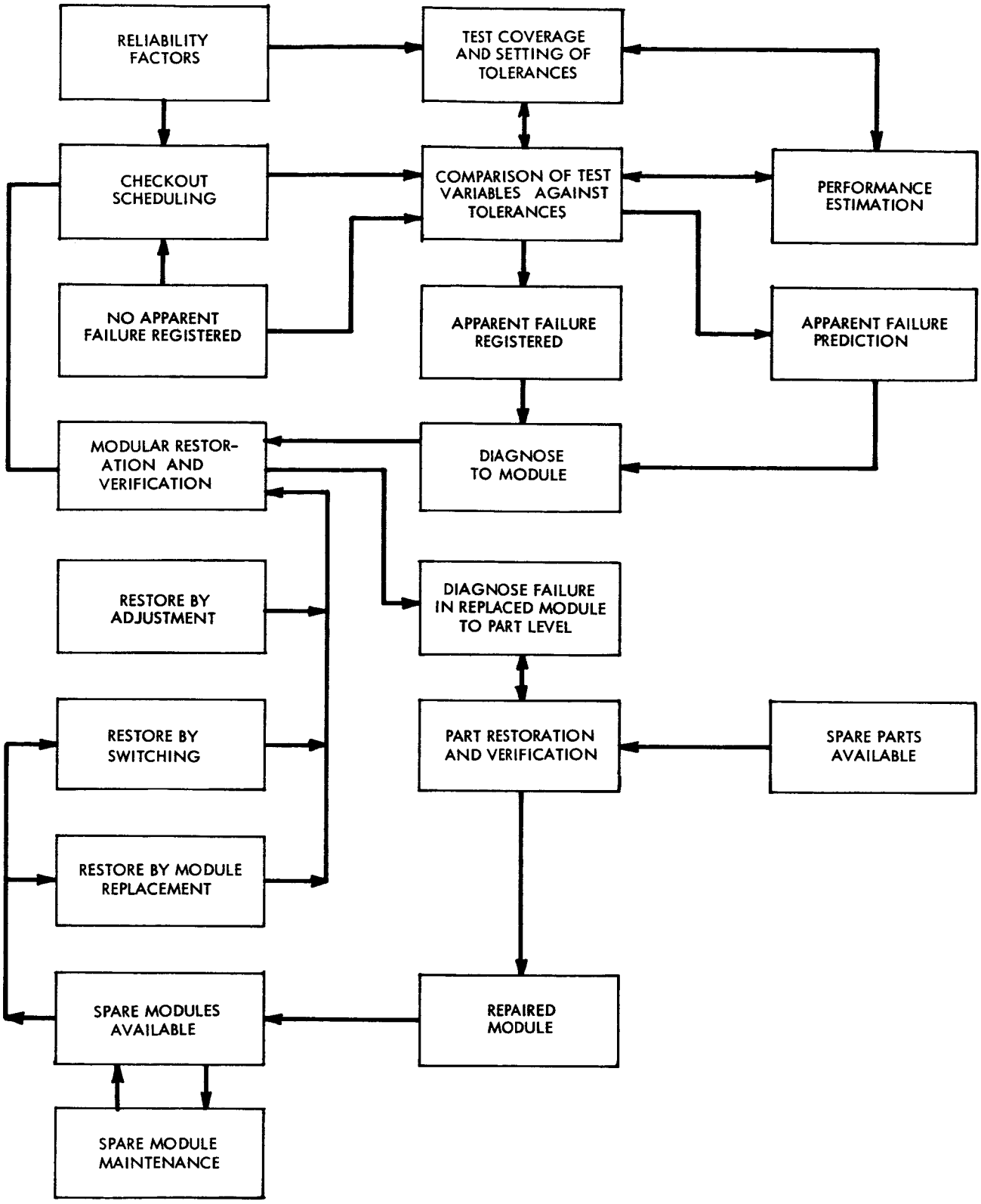

Figure 1. Typical Elements of Operational Status Control

provide perfect guarantees of fault detection. Furthermore, complete testing of all functions may not be desirable from an overall cost-effectiveness point of view.

Even with incomplete coverage of all functions, the unobservable failures will eventually be replaced, whenever a fault in the observable part of the same subsystem is registered and the subsystem module is replaced. The registration of faults by the checkout equipment represents, however, only registration of apparent failures in the observable portion of the subsystem under test. The tests also include possible Type I and Type II errors; i.e., possibly calling the measured part good if bad, or bad if good. It should be noted that the probability of accepting a bad system can be caused by either a test error or a lack of test coverage.

Further aspects on the design for testability will be covered by Peterson in the next section.

Tolerance Limits. Tolerance limits can be considered as the limiting boundaries of allowable variation in the characteristics of a given subsystem. The purpose of tolerance limits is to partition the set of possible values that a test variable can assume into two subsets: within tolerance and out-of-tolerance. Then, tolerance limits provide a basis for selecting required maintenance actions, if any.

Tolerance limits can be set on the following types of quantities:[2]

1. Performance Figures. Variables which represent a performance figure or index relating to a mission to be accomplished. An example is the mean-squared error of the actual output from the desired output.
2. Transfer Characteristics.[3] Variables which represent the input-output relations in either the frequency domain or the time domain.

3. Properties of Transfer Characteristics. Examples of variables which represent properties of transfer characteristics are bandwidth, rate of cutoff, delay time, overshoot, rise time, and settling time. These variables are known through engineering analyses to be strategic in assuring satisfactory performance of a subsystem.

4. Internal Quantities. Examples of variables which represent internal quantities are power supply voltage, impedances, etc.

For checkout purposes, it is standard practice to assign tolerance limits to subsystems or components, given system tolerance limits. Techniques exist for setting tolerance limits on all of the above type quantities, 1 through 4, Once set, tolerance limits provide a basis for making decisions on what should be done to the subsystem. If a characteristic is measured to be within tolerance, no malfunction isolation and repair activities will be initiated, and vice versa.

Checkout Scheduling. Checkout scheduling might be continuous, periodic, or contingent, or a combination of all three alternatives, depending upon the expected benefits and penalties. One important criteria to use in choosing among alternative checkout schedules is to choose the schedule which maximizes readiness for a given operational cost, or which minimizes the operational cost in attempting to achieve a stated degree of readiness. Included in any realistic analysis of optimal checkout scheduling must be the effects of test coverage, imperfections in checkout and repair, opportunistic or contingent testing, test stresses imposed, expected duration of service times, failure distributions, etc.

Comparison of Test Variables Against Tolerances. The test variables or attributes are compared against tolerances to evaluate the system status as well as to predict failures and make performance estimates. The results of a comparison can indicate the existence of a NO-GO situation, or an impending failure, or the ability of the system to perform a given mission. On the basis of these comparisons,

decisions are made such as to undergo fault isolation, to continue present status, to abort, or to change to alternate mission modes.

Performance Estimation. In general, a performance estimate could be considered as a quantitative estimate of the operational capability of the system to perform its mission tasks. As such, two methods can be employed for performance estimation: 1) simulation, and 2) measure-compute.[2] In the first approach, the prime equipment participates directly in the simulation. In the second approach, the prime equipment responses are recorded and the prime equipment is not involved in the subsequent computations. One advantage of the first approach is that there is no problem of representing the characteristics of the equipment involved. The practicality of the measure-compute approach depends upon the effort required for measurement and response processing. This task is more difficult for nonlinear systems than for linear systems, but there are many systems whose normal operations can be described with sufficient accuracy by a linear characterization. It must be noted that in either approach, the overall system performance must be related somehow to the subsystem performance, in order to establish the allowable variations in the characteristics of the subsystems.

A malfunction or fault can be defined[4] as an excessive abnormality in a part of an assembly that controls the system's present or future performance, relative to a standard or successfully operating unit. An abnormality is a potentially measurable and significant deviation from a standard. The abnormality becomes a fault when some internally based physical or electrical characteristic is outside normal operating limits. The limits can be set, after the "normal" parameter range is defined, by virtue of having seen one or more units perform their mission or pass a qualifying test. The limits can be set at a point just beyond normal parameter excusions under field test conditions, regardless of whether the overall performance

is noticeably affected. Alternatively, from a set of measurements which are synthesized by a vehicle parametric design approach[5], limits can be categorized according to performance calculations using this novel approach.

When a subsystem is said to be operating within its tolerance limits, there is implied the condition that realistic inputs exist. For example, ambient temperature extremes as well as unwanted stresses are realistic, if not typical, inputs. Even if no component failure exists, by definition a fault exists whenever an out-of-tolerance departure from a prescribed transfer function occurs. This means one or more internal parameters are out-of-tolerance. On the other hand, an internal parameter out-of-tolerance may not cause the corresponding subsystem transfer function to be out-of-tolerance. Consequently, for both failure detection and failure isolation, one must determine the groups of symptoms that are sufficient to characterize uniquely a failure or potential failure.

Since the realistic tolerance limits for some subsystem transfer functions may be somewhat dependent on the performance characteristics of other subsystem transfer functions, establishing infallible tolerance limits for certain subsystem transfers will be next to impossible. Thus, there will exist possibilities that fault indications will occur for a particular subsystem transfer function, without there actually being significant overall system performance degradation. Obviously, highly accurate monitoring of the overall system transfer functions would constitute a self-check on as well as a basis for the entire set of subsystem tolerance setting, fault detection and isolation processes. Such overall system performance analysis can be accomplished by the generalized parametric design approach described in Reference 5.

Register and Non-Register of Apparent Failures. As conceived above, a given system can be thought of as composed of two distinct parts. One part will fail in a manner that can be detected by the testing procedures, while the other part fails in a manner that is not detected by these procedures. When the unobservable part has failed, the system is down and remains down until the observable part is called bad and eventually restored by a good system. Since a faulty system may be replaced with another faulty system, the restoration period may last over several replacements. The average restoration time, T_R, is the average time from the start of repair to the restoration of the system to an up condition.

Periodic checkout is testing for failures on a periodic basis. Strictly speaking, "periodic" checkout is sequential and not truly "periodic" in a calendar sense. The occurrence and duration of service times will vary statistically, from time to time. For convenience, however, the term "periodic" is used. In between these tests, the system is in a standby-deployment interval of duration T. (See Figure 2). At the end of the standby interval, the system is tested to assure that it is up. Because of testing errors and imperfect test coverage, however, each periodic checkout leads to uncertainties in determining the true status of the system. Furthermore, additional test stresses are imposed during periodic checkout and the system is running during most of the checkout time, even though the test decision occurs over a small fraction of the total running time. The consequences of these realistic factors, which occur for periodically checked systems, can be formulated and used to evaluate and optimize the readiness of periodically checked systems.

The detectable part of a given system may be called bad when it is actually bad or good. The test efficiency E is the probability that a system which is detectably bad will be called bad by a single application of the test. The false alarm probability α is the probability that a system which is detectably good (regardless of the

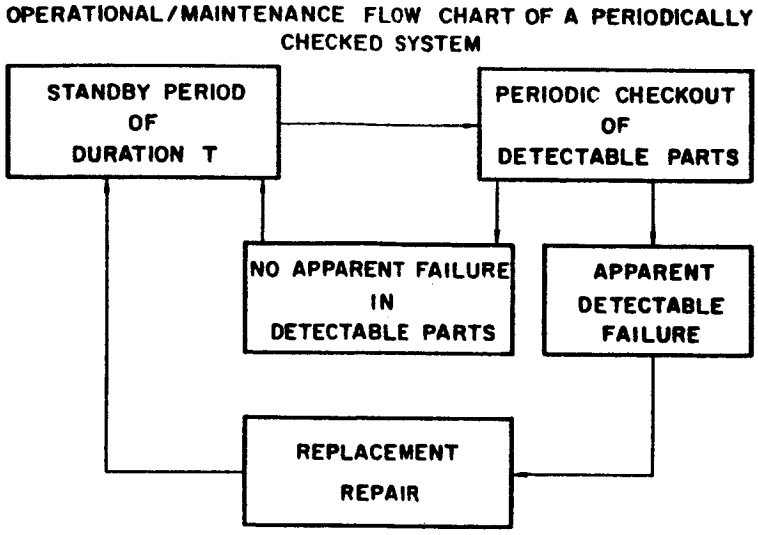

Figure 2.

condition of the undetectable part) will be called bad by a single application of the test. Thus the effect of a single test decision might be represented by one of the eight possible results shown in Figure 3 below.

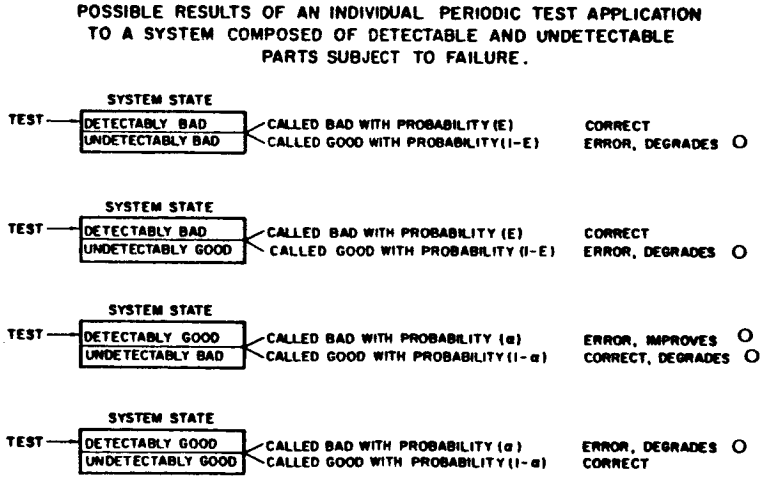

Figure 3.

Apparent Failure Prediction. By internal parameter testing,[6] "the failure information content of test data can be maximized as opposed to reconfirming transfer functions by end-to-end testing." Accordingly, internal parameter testing can be utilized to predict future performance as well as to indicate status at the time of test. For example, servomechanisms are relatively insensitive to abnormalities within the closed loop because of the inverse feedback used. Consequently, points inside the loop must be tested to assess the real status. By identifying failure symptoms, such as leaky capacitors and hot transformers, before the gross failure (shorted capacitors or transformers) occurs, internal parameters and characteristics can be checked with sufficient accuracy to determine whether or not failure conditions exist.

Although this process doesn't insure detection of all potential failure modes, internal parameter testing can go a long way in improving status control. The availability of precise failure distribution data as well as knowledge of failure mechanizations may be questionable at the moment, but the ability to acquire better failure data by internal parameter testing in the vicinity of likely failures seems well established. This methodology offers much promise for future improvements in system readiness programs.

In general, failure prediction methods effectively increase the MTBF but may also tend to increase the false alarm probability. Such a tradeoff would have to be made in order to optimize the feature of failure prediction in increasing overall system readiness.

Failure Diagnosis to Modular Level. Realizing that the limitations in performing automatic fault isolation is not in equipment capability but rather in the method of use, one objective is to provide a better rationale for the design of optimum test procedures. Greater flexibility in test programming can be obtained by utilizing the true computational capability of a high-speed computer. For this

purpose, a generalized fault isolation technique is preferred which makes full use of computerized logic to acheive optimal test point and data selection for practical and efficient fault isolation. By this approach, tradeoffs between input stimuli, measurement parameters, choice and number of test points, and percent of fault isolation can be examined, and the optimum combination determined automatically. In general, techniques for fault isolation could be grouped as:[7]

a) simple branching
b) information state techniques
c) solution of simultaneous equations
d) pattern matching

Simple branching is the technique that is being presently used, whereby a test diagram is constructed that describes how tests should be sequenced, depending upon the outcome of each subsequent test. Although easy to implement, the excessive storage demands and search times required make it relatively inefficient, especially for complex systems. As such, this approach might be considered as a computerized, clerical version of manual test operations, not taking advantage of the true capability of computers.

In implementing sequential tests, a figure of merit approach, based on simple information theory or similar criteria, can be used in the decisions for test selection. After such test, based upon the new information obtained, new figures of merit are calculated, and so on.

Information state techniques take advantage of computational capabilities to reduce data storage requirements. Partial fault isolation is obtained by Boolean functions corresponding to each test and its result. The partial isolation is continued until the actual fault mode is identified and isolated. Again, this is a method essentially for test selection and does not presume to be optimal in the sense of test point selection, stimuli, etc., but is an extension of computerized manual approaches.

The technique of solution of simultaneous equations uses analog data directly, permitting determination of the component values by solution of simultaneous network equations. Transfer admittances of circuit networks, for example, can be measured by applying voltages between selected nodes and measuring the outputs at other nodes. If enough test points are available, the values of the components within the network can all be determined. These values can be compared with the design values and predetermined tolerances to detect and isolate faulty components. The entire process can be performed automatically on a digital computer to calculate from and maintain control over the measurements. Unfortunately, there are several limitations to this technique. The inverse solutions required, especially in the presence of nonlinear and/or active elements, greatly complicate the process and the solvability in real time becomes excessively tedious, if not impossible. For a complex circuit, the mathematical analysis would be extremely long and complicated. Yet, there are possibilities with this approach that could be developed if inverse solutions were not required, which brings us to the preferred technique described next.

The pattern matching, or pattern identification, or test diagram technique, as it is sometimes called in the literature, is basically a comparison of measured voltage patterns with precalculated voltage patterns that would exist in the event of faulty elements. As a concept, the pattern matching technique enables much of the analysis to be done prior to actual fault isolation. The test pattern is matched against known patterns in the computer library which appear as fault modes in the information state technique. The difference is that in the pattern matching techniques, all the required tests are applied and all component values of the pattern are compared simultaneously.

Although this technique has been recognized as useful for digital circuits such as logic machines, it apparently has never been fully

developed for use on analog circuity. A major problem in employing this technique has been developing a set of tests that would thoroughly isolate the various failure modes. An intriguing aspect of this technique, however, is the feature that the cumbersome inverse solutions, when applied to analog circuits, are obviated.

The methods to be used for test point selection and for fault isolation can be based on an extension and generalization of pattern matching techniques that have proved to be useful for digital machines. The "patterns" involved would be test measurements available at the test points under given stimuli. The aim of the test point selection procedure would be to choose the set of test points that maximizes a measure of the usefulness of "distinguishable" patterns while minimizing the "cost" of such a test point set in terms of its size, the number of necessary test stimuli that must be applied, etc. The fault isolation procedure can utilize the patterns generated in the test point selection procedure to make its first pass to determine possible fault candidates. On the basis of its narrowing the field of possible faults, the computer program can then generate a set of sharper tests to isolate the true fault, as far as possible, from among these possibilities.

The chief advantages of this generalized method would appear to be the essential simplicity of the computer programs required for it, and its compatibility with the memory storages of present generation computers. In each phase of the analysis, the computer need only perform certain systematic and predetermined transformations on the test parameters. The evaluation matrix carries out the required comparison of measurements.

Module Restoration. The effect of imperfect restoration in determining the expected restoration time will now be considered. An attempted restoration can end in one of the four conditions represented in Figure 4. The probability of a "good" repair, i.e., condition I,

is denoted by r_1, while the probability of a detectably "bad" repair, i.e., condition II or III, is denoted by r_2.

If an attempted restoration results in condition I, the system has been restored to an "up" condition. If, however, the attempted repair results in condition II or III, a "down" system (apparently "up") is returned to standby, and it must be called "bad" during a subsequent checkout before another attempt at repair will be made. Finally, if the repair attempt results in condition IV, a "down" system is again returned to standby. In this case, the system is apparently "up" and the failure in the system is undetectable. Therefore, no attempt at repair will be made until (1) the occurrences and subsequent detection of a detectable failure, or (2) the occurrence of a false alarm on the "good" detectable portion of the system.

Spare Module Availability and Maintenance. The condition of the replaceable spare modules strongly influences the overall readiness, since it will affect the restoration probabilities, r_1 and r_2, as well as the expected duration of the true restoration period. Consequently, it is highly desirable to consider the applicability of the checkout process down to the spares level, where the readiness of the spares as well as the storage of adequate spares is important in maintaining the desired degree of prime system readiness.

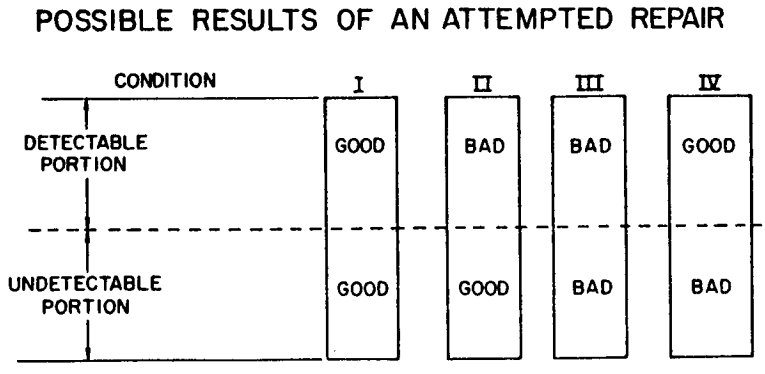

Figure 4.

Part Level Diagnosis and Modular Restoration. High system readiness places a requirement for rapid detection to some functional level less than the system level, but at a cost. Replacement of a failed module at an operational level increases system readiness but raises the costs of spares. Depending upon overall system cost-effectiveness, it may be desirable to repair the modules onboard, or in the vicinity of the prime system, rather than to discard or ship the faulty modules back for repair. Use of the same diagnostic procedure for spares restoration, as well as proper selection of the replaceable module size, is but one example of the many tradeoffs possible to optimize overall cost-effectiveness.

Expected Down Time Factors. Essentially, the prime system is considered down or non-available for immediate use when engaged in any off-line maintenance or service that puts it out of commission. It may be unavailable due to periodic checkout, planned or unscheduled maintenance, including being out-of-commission for lack of available spares. Statistical techniques, such as extensions of queuing theory, can be used to handle the specific down-time distributions and variances.

The finite-population queuing problem, where service is assumed to be available on a continuous basis, has been extensively investigated. An important aspect of many queuing problems met in practice, however, is that service is only available periodically, such as on one eight-hour shift out of every twenty-four hours. In applications where "arrivals" or "failures" occur on a continuous basis, the effect of such an interruption in service can be of great interest.

Assume, for example, a system composed of N units and S service channels, where the service channels are available periodically for the first R hours out of each T hours. It will also be assumed that each of the N units have a "failure" or "arrival" distribution which

is exponentially distributed with a mean time between failure per unit of M hours and that each of the S service channels have a exponential distribution of servicing time with mean of H hours. Units that fail are serviced on a first-come-first-served basis, and the total time to service a unit is not affected by any interruptions in availability of service units. A unit which demands service and has not been completely serviced is considered to be in a "demand" condition, while a unit that demands service and is not actively being serviced at the moment is considered to be in a "waiting" condition. Thus, in the period when service is unavailable, all demand units are also waiting units. A unit that is not a demand unit is said to be operating or idle, etc., depending on the application.

Figure 5 illustrates the results[8] of these computations for multichannel queuing with periodically interrupted service. These results are plotted for a population N = 150 units, mean-time-between-arrivals M = 700 hours. Figure 5 illustrates the corresponding mean queue time (waiting for service or being served) versus crew number. The details of this study are given in Reference 8.

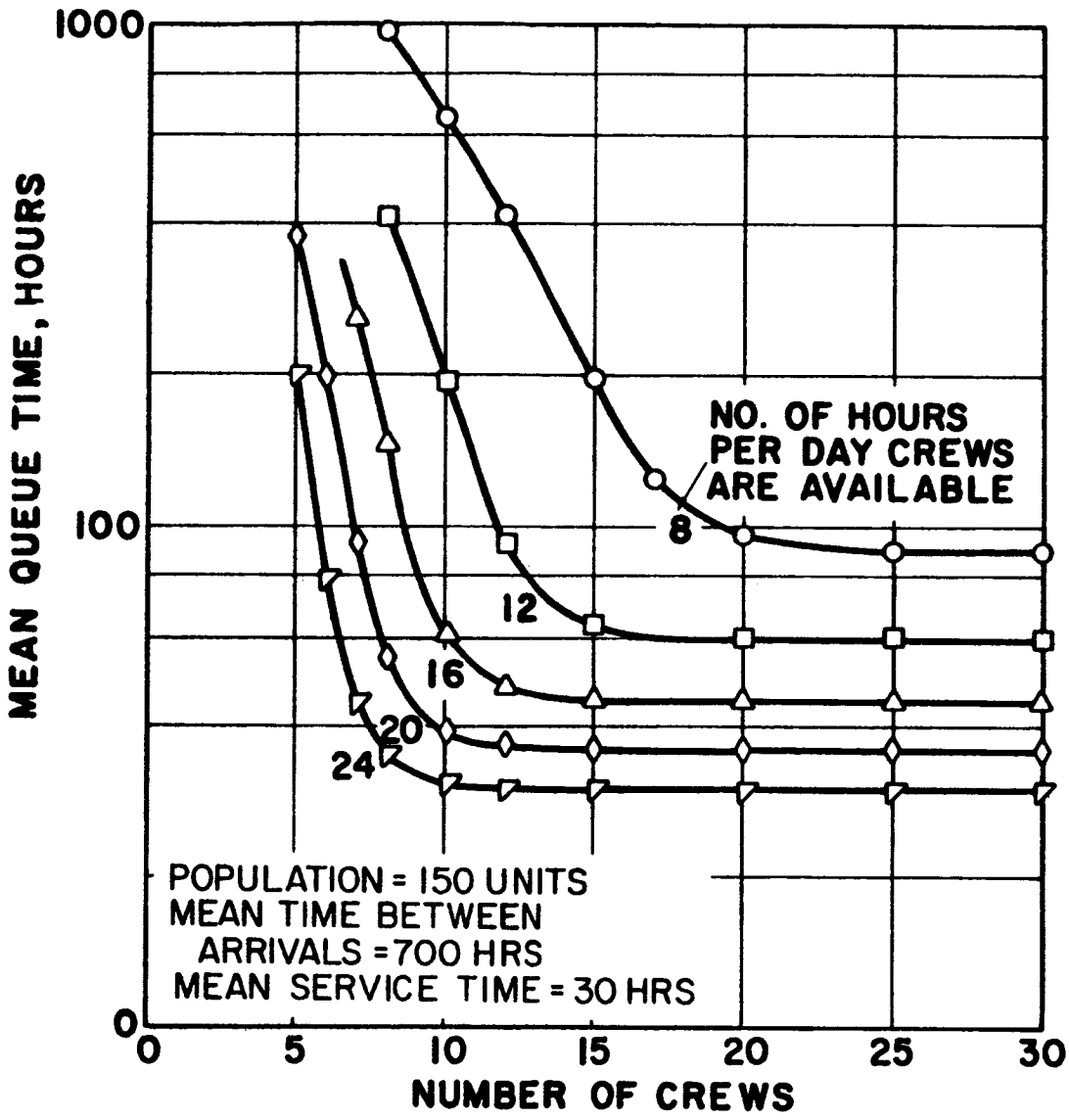
1000
100
0
MEAN QUEUE TIME, HOURS
NO. OF HOURS
PER DAY CREWS
ARE AVAILABLE
8
12
16
20
24
POPULATION = 150 UNITS
MEAN TIME BETWEEN
ARRIVALS = 700 HRS
MEAN SERVICE TIME = 30 HRS
0
5
10
15
20
25
30
NUMBER OF CREWS

Figure 5.

V SUMMARY

The attempt was made to point out some of the major areas involved in operational status control and how they are interrelated. In general, all the areas might be categorized in terms of how they contribute to system up time and system down time. Obviously, all areas are related to overall system effectiveness, and each area has both controllable and uncontrollable factors. It was the purpose of this paper to point out how the controllable factors could be traded-off in order to optimize system effectiveness, which, of course, would depend upon the specific application or mission. In particular, an extensive series of operational reliability models have been developed[9-17] at STL, RAND, and elsewhere, which have established many of the essential tradeoffs. Data management techniques[18-22] have also been developed to generate estimates of the operational and hardware parameters involved. Such models have been developed and utilized for ballistic missile system management on Atlas, Titan and Minuteman and have also been developed for other aerospace applications, manned and unmanned.

Generating realistic system models which truly represent the system under consideration must first involve a sound understanding of the system functions and their interrelationships. It is contended that as the complexity and pace of aerospace systems increase, such models become mandatory management tools for properly planning, designing, and evaluating the role of automatic checkout.

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TITLE: THE SYSTEM APPROACH TO AUTOMATIC CHECKOUT - PART III

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1.0 CHECKOUT PHILOSOPHY

1.1 Introduction

The modern aerospace military weapon and exploratory space probe vehicle systems are composed of many highly complex and interdependent subsystems. In order to successfully accomplish the mission for which the system is designed, it is necessary that each subsystem must accurately perform its apportioned part of the total mission. It is a primary function of system checkout to determine whether these subsystems integrated into a fully-assembled system are operating within prescribed tolerances and that all electrical interfaces between missile stages and with external circuits are proper, or if not, which element is failing in its assigned function. An additional requirement is placed on checkout - the determination of possible incipient or future failures. The justification for existence of checkout equipment in both ballistic missile and space flight programs is the increase in confidence and actual reliability gained through the use of this equipment that the vehicle will successfully meet its flight objectives. The more successfully the checkout equipment accomplishes these functions, the higher will be the probability that mission objectives will be met.[1] Through properly engineered automated techniques, these functions may be readily accomplished. A systems approach must be taken at the initiation of the vehicle design phase in order that support operations may not complicate the vehicle system to an extent that a lower reliability level may exist.

The integration of two pieces of equipment, such as a test equipment to its prime is a two-way street. Not only the so-called checkout requirements of the prime equipment need to be examined, but also the available checkout capabilities[2]. In this case, the substantial improvement it is believed the art can provide, is a result of the combination of a prime system designed for testability and application of a high-speed data processor type of automatic checkout equipment (ACOE).

In the majority of cases the larger and potentially less reliable systems are divided and procured in various large pieces. Since each contractor must be given full responsibility for his work, it follows that there has been a tendency to check a complete vehicle system on a non-integrated basis, except perhaps for over-all parameters. This combined administrative and engineering question of how to plan for a commonly used integrated system test program and the single large ACOE necessary to implement it while still permitting each of the contributing contractors and designers maximum leeway to perform their tasks defies easy solution. One answer of merit is to separately contract integration and checkout responsibilities including meticulous coordination of test plans with the prime equipment designers.

Before any design of checkout equipment may begin, an understanding must be reached in the identification, definition, and classification of various aspects of the Testing discipline as related to a particular program under consideration. The Testing discipline may be divided into four principal categories as follows: (See Figure 1)

- o Test philosophy
- o Test methods
- o Testing operations procedures
- o Data interpretation

1.2 Establishment of a Test Philosophy

Test philosophy may be defined as a "statement of the information which is to be acquired as a result of testing and what is to be done with this information[3]." The effort required during the development of a test philosophy includes the areas of functional analysis, prime equipment design for testability, and a definition of applicable test techniques.

During the period when the functional analysis is being accomplished in an entire ballistic missile or space probe system, a definition of the prime equipment to be tested, the establishment of a test flow program, and a complete definition of the capability requirements of the checkout equipment is accomplished.

1.3 Test Methods

Specific testing methods or techniques are defined as the various methods of implementing a test philosophy and acquiring data from the article under test which have been employed in recent years and include the following:

- o Single stimuli testing including complex waveform and noise
- o Transfer function analysis
- o Marginal testing
- o Radiation stimuli
- o Continuous monitor methods
- o Monte Carlo or controlled random

1.4 Test Operations Procedures

This category includes the mechanization of selected test methods, including test procedure and data gathering operations. Examples of this mechanization would include the following:

- o Signal tracing - An introduction of stimuli signals with measurements made of responses at various points in the equipment under test along the signal flow path.

- o Parameter Measurement - The measurement of circuit parameters (voltage, impedance, etc.) at components, circuit junctions, modules, systems, inputs and outputs.

- o Functional simulation - Use of simulation to provide normal values to evaluate proper operation under varied conditions, with comparison between simulation and equipment under test.

- o Abnormal operation - Evaluation of the equipment under test over environmental ranges greater than normal.

- o Sensory evaluation - Stop, look, smell.

The decision of degree of automaticity in checkout operation falls in this category, that is whether the test method employed is implemented through manual, semi-automatic, or fully automatic checkout (ACO) techniques.

1.5 Data Interpretation

This fourth category includes the following areas of the testing discipline:

- o Interpretation of test data - The generation of information on the readiness of the article under test through an analysis of the test data.

- o Fault detection - The detection of any faults present in the article under test during the time of test as evidenced in the test data.

- o Fault isolation - The location within any portion of a system as defined in a maintenance plan of a fault present in the test article during the time of test as evidenced in the test data.

- o Fault prediction - The information gained from the test data of an impending or incipient fault along with information as to isolation and approximate time of future failure.

- o Figure of merit - A determination of the relative excellence of a particular unit under test as compared to a standard or normal of other units.

- o Feedback to test philosophy - A control function whereby a test philosophy may be modified as a result of the information gained from the logical interpretation of data from the article under test.

Test evaluation systems are included in data interpretation and are defined as the data processing function of the checkout equipment which accepts and operates on the data from the vehicle under test to make decisions as to whether the vehicle is performing properly. Output from the evaluation system is directed to display and recording portions of the checkout equipment as well as back to the programming area. In a fully automated set of checkout equipment, the primary information presented, of course is GO or NO/GO readout for the checkout equipment and unit under test. In the case of manual type equipment, the operators serve as part of the evaluation system.

1.6 Aerospace Equipment Checkout

Fundamentally, all types of checkout equipment are similar in basic purpose and in the major functions performed, whether designed for a ballistic missile or space probe program. This equipment entails three basic functions which may be labelled as follows:

a. Input Stimuli
b. Output Data
c. Test Control

The input stimuli are those signals impressed on the test article in order to generate predicted responses. The output data are the responses by the test article and assessment of these responses. Test control is the programming and sequencing of the input stimuli, output data, the test equipment, and unit under test. These functions are associated in a loop with feedback as shown in Figure 2.

A comparison in requirements and capabilities in the checkout equipment designed to support Ballistic Missiles to those for orbital or space vehicles discloses several important differences, some of these and the necessity for them being fundamental and considerable, while others are not as extensive or immediately apparent. The requirement for unscheduled launch, the relatively fixed design, and operation by unskilled personnel in Ballistic Missile programs, are given as examples.

Probably the strongest factor affecting the history of design of support equipment for exploratory space probes has been the fact that over-all vehicles for these missions have been unique. Unlike flight tests of ballistic missiles, few space probe flight tests have been made up to the current time with the same objectives. Each was individually tailored to specific test objectives. The methods used in the attempt to meet a given objective also has often changed radically from one vehicle to the next. In general, this has had great affect on ground support equipment requirements, as changing the intent of a space probe mission means changing spacecraft payload, the missile staging, and trajectory, and therefore, a revision of the entire launch plan. In large measure, this is still the case and is likely to be true for some time to come.

Space probe support equipment must therefore be extremely versatile and flexible. Changes in instrumentation in order to monitor a new function are often required on short notice. New requirements or trajectory limitations may impose a special fitting on a handling fixture for the payload, or the installation of an electronic assembly with additional test points involved. The continual need for equipment modification during the process of an R and D program requires that support equipment be amenable to change without undue schedule delay or extensive cost, sometimes a few hours before launch.

Currently in the United States programs of space exploration, we are entering into a period of spacecraft development in which basic structures will be used for numbers of different payloads or sets of scientific experiments[4].

These universal spacecraft or "work horses" will be used in widely varied combinations of earth orbit, cis-lunar, lunar, and interplanetary space explorations. In programs where these spacecraft are used, because of similarities in communications, control, propulsion, and electrical systems, the use of automatic checkout equipment for evaluation of similar spacecraft units becomes increasingly attractive. These facts both permit and require significant improvements in the area of ground support equipment for each succeeding spacecraft, particularly in the areas of integrated systems test and pre-launch evaluation. These improvements will permit the use of the most recent techniques in data encoding, handling, and storage.

In the evolutionary phases of manned exploratory spacecraft planned in the foreseeable future, whether they are for orbital, lunar, or planetary flights, operational quantities, i.e., number and schedule of vehicles, will require flight line type of automatic, rapid test, and ultra reliable checkout equipment. Very similar equipment will be required for detailed factory acceptance testing, pre-launch checkout, and for short confidence tests of recovered or reusable spacecraft. These future requirements can be met in most part by automated checkout equipment. This ground equipment will be used in conjunction with flight on-board maintenance and checkout devices[5].

The direction of future development of ground checkout equipment for manned spacecraft missions will depend to a relatively large extent upon future design of on-board maintenance and checkout equipment. This will enable the crew of such spacecraft to assess the condition of the spacecraft electronic equipment during the course of the mission, to monitor critical parameters and to effect an adjustment or repair/replacement sequence as required. The key element in an on-board maintenance system remains the crew. The crew personnel are able to contribute highly to the over-all mission reliability through their capability of analysis and judgment which far surpasses the most sophisticated automatic evaluation systems. The first role of on-board maintenance and checkout equipment will be one of tolerance limit evaluation with limited fault detecting capabilities on the functions which are either displayed to the personnel aboard or transmitted to ground receiving stations. The secondary function is the ability to provide precisely timed sequence of events such as those required in a lunar launch countdown as well as certain in-flight manuevers.

The on-board maintenance system then will be required to have the following capabilities:

a. Provision of assistance in earth pre-launch confidence checks. On-board maintenance limit comparison with expanded storage memory, may well replace most ground test functions. The task of the automatic ground equipment will then be limited to input programming, application of external stimuli, and the final presentation and recording of test results. Fixed test programs and fault isolation routines may also be eventually stored in the flight equipment memory. The earth based ground equipment will probably continue to include a

wider range of stimuli and programmed exercise of the vehicle electronics, but a larger percentage of identical testing is anticipated to be incorporated in the on-board equipment of the spacecraft in the future. Hardware for on-board maintenance system, therefore, is provided where time limits crew activities during some phases of a mission. All RF transmission links should be capable of being exercised as in-flight during pre-launch evaluation, including crew communications with actual receiving stations.

b. Provision of lunar or planet pre-launch checkout and launch sequencing. The major percentage of checkout which is accomplished at the integrated system test level and just prior to launch may be transferred from the ground equipment to the on-board spacecraft checkout equipment. This will allow extensive checkout of the vehicle with the on-board maintenance equipment using a common checkout procedure; for example, prior to leaving the surface of the moon or planet on which the vehicle has been landed.

c. Provision of pre-determined sequences of action involving critical timing, as stated.

d. Relief to crew members of the necessity of continuously monitoring a large number of sensors and test points.

   Each decision-making or computing device existing for on-board control should therefore incorporate self-check capabilities and procedures. The crew must have the facility of program override during confidence checkout procedure, as well as manual control of the test program, in a similar manner to the operator of ground-based automatic checkout equipment.

e. Usage of flight in-line equipment.

   The on-board maintenance equipment must make maximum use of the programming and test capability of existing on-board computers such as will be provided for navigation, guidance, or stabilization. It should have nominal closed-loop checkout routines for each subsystem or logical series connection of subsystems and systems.

f. Mission success enhancement.

   The probability of crew survival and mission success through all phases of flight would be maximized by checking equipment sufficiently in advance of use to allow appropriate actions to be performed in the event a malfunction is indicated.

2.0 PRIME EQUIPMENT DESIGN FOR TESTABILITY

2.1 Definitions

The prime equipment must be "designed for testability" which means that the checkout requirements must be considered during the initial prime equipment design phase. The testing discipline must be considered as a part of the over-all system in initial analyses. This consideration requires integration and liaison work with the test article designers, a quantitative failure mode analysis in the prime equipment, and trade-off studies between test requirements and vehicle readiness states throughout the program.

The term "design for testability" is used to denote an approach to prime equipment design which will result in optimum evaluation of performance of the prime equipment at all levels of test through the complete mission. In order to successfully effect these accomplishments, the following factors must be taken into consideration:

a. The analysis of failure modes within a system, analysis of checks required and procedures to test for the failure modes.

b. Design for testability must be done on a quantitative basis. The basic numbers involved are prime system reliability, failure rates, and mean time between failure (MTBF). Also involved in the numerical trade-offs are test time, test frequency, weight, cost, undetectable potential failures, and failure content of test data.

c. The special physical provisions related to maintenance and testing are included. Some are conventional and well-known such as good access, modular construction, proper isolation of monitored circuits, etc. Additional connections may be placed on circuits or junction points not heretofore measured, and occasionally, installation of flight equipment which is required exclusively for test and evaluation. The physical results of this approach are lots of generally small but important details which must be provided for in initial design and cannot usually be retrofitted. Examples include:

Wiring
Integrated isolation and multiplier resistors
Inductive and capacitive pick-ups
Instrumentation and signal conditioning circuits
Brackets
A magnetic data readout device such as a metal tape to identify the prime system and its configuration
Inter-assembly test and umbilical connections

d. To design a prime system for testability one must know the system circuitry and the way it is intended to work in minute detail, the test objectives, the general principles of designing for testability, and the capabilities of check-out equipment. As an example, it is not possible to plan to do fault isolation on a large system without providing a logical capability.

e. Much of the actual work must be performed by the prime equipment detail circuit designer in accordance with established system requirements. He must be educated on how to proceed so he will select required test points which provide detailed fault status information, not merely to reconfirm his design parameters.

f. The analysis during prime equipment design for testability to permit maximum utilization of checkout procedures would include the following steps:

(1) Parts, circuits, and network counts
(2) Consideration of circuits and their application, including environmental factors
(3) Parts failure mode analysis including rates for modules as well as parts
(4) Consideration of consequences of failure or partial failure
(5) Selection of test points, stimulus points, and instrumentation to make required measurements based upon probability of failure and sensitivity of the possible test points to the failures.
(6) Selection of isolation means to prevent trouble in test provisions from affecting prime system performance.
(7) Consideration of ability of now available data to effect fault isolation to the desired level, adding test points needed for this purpose.
(8) Consideration of functional packaging for simple and conclusive fault isolation.
(9) Examination of test points now available for secondary test data which can be wrung from the same set of points. Examples of this might be to measure resistances of all points to ground or look at the points as network terminals which can be used to verify configuration of the network.

2.2 Procedures

What we mean by design for testability can be concisely described in terms of what is done and the physical results of the action. The design analysis phase results broadly in documents and charts which:

a. Define the test modes requirements, and conditions.

b. Establish instrument requirements and instrumentation for the mechanical and electro-mechanical components.

c. Select the test points in the electronic components.

d. Provide the fault isolation logic and define the data necessary to implement it.

e. Establish the complete program of measurements and stimuli and the order in which they are performed.

A test program chart which calls out in detail the test modes, requirements, and conditions is first generated in broad terms at subsystem level and refined and integrated into a complete system program by stages. It ultimately completely specifies the test program, including all measurements, stimuli, and test order.

Mechanical and electro-mechanical subsystem and components generally require instrumentation to secure test data. The instrumentation and test point design is implemented through a system logic chart which then defines the tests that are made and the result-dependent branch points. More important, however, because of the relatively high susceptibility of electronics to failure, is the test point and failure detection measurement selection which become a part of the test program chart.

Having considered broadly the more important design approaches to design-for-testability, we now consider briefly what comprises the physical results. An inherent part of the approach is that the system to be tested must have built-in a series of small but important test provisions. These design provisions are listed in Table I.

TABLE I

DESIGN PROVISIONS FOR TESTABILITY
IN PRIME SYSTEMS

a. Integrated transducer type instrumentation

b. Test and stimulus point terminals

c. Wiring to provide external electrical data access

d. Connectors

e. Isolation devices

f. Conversion and data conditioning devices

g. Appropriate bracketry, routing channels, etc.

h. Electronic component functional allocation and packaging designs to permit conclusive failure isolation.

There are several strong guidelines which govern and explain the philosophy behind these provisions:

Weight

Airborne or launch weight in Aerospace systems is expensive and test devices not involved in the primary operation belong on the ground insofar as possible. On the other side of the coin, a comprehensive checkout is required to promote maximum reliability of the mission. Lightweight instrumentation and auxiliary devices, together with wiring to bring the test data out to a processor which is large enough to handle it properly, is the best trade-off. Considerable data can be routed out of a system via lightweight cabling of the types shown in Figure 3 for a surprisingly low weight penalty. In some cases it can be made a part of a multiplexed telemetry system and therefore involves no additional penalty.

Instrumentation

Where possible, it is advantageous to integrate the instrumentation into the replaceable component tests by the same standards and methods at all points in the component flow.

Isolation

Another ground rule in design-for-testability is to monitor the prime system without the possibility of affecting it through circuit loading or noise insertion, and avoiding reliability reduction by adding the failure rate of the test provisions. This involves some form of isolation which, in electrical or electronic subsystems, takes the form of a series isolation resistors or diodes fabricated directly into the test point output. Another illustration of isolation means the pick-up coil in Figure 4 which provides shaft motion. This design also illustrates the multiple use of an instrument since the coil is also used in another test mode to stimulate motion in the valve. Protection against accidental stimulation may not be needed, but if it is, it can be provided in several simple ways.

Conversion and Data Conditioning Devices

The general rule is to perform data conversion outside the prime equipment where weight is relatively cheap. There are a number of cases, however, where almost negligible added weight produces important test data which would be otherwise not available, or may result in a reduction in weight of the cabling. Diodes to convert high frequency a-c to d-c, or a shunt resistor to ground, which, together with the isolation resistor divides down a high voltage, are simple examples of such devices. A more complex example is the case of high ohmage resistors to several contacts on low voltage relays to form logical networks which perform the dual functions of isolation and multiplexing several relay states to a single conductor. Increased application of microelectronics will extend these possibilities. Assuming that projected reliability figures for this method are realized, the problems of signal conditioning, isolation, and interconnection, as well as quantity of circuits, physical size, and weight problems, should be substantially reduced.

Test Point Selection

Test points are typically used for various measurements, for applying stimuli, and for circuit conditioning; e.g., grounding. The quantity of test points required to implement this approach to testing in a modern Aerospace system will necessarily be large. One method of accomplishing data transmission from the prime to the test equipment is by means of electronic scanning or multiplexing. Obtaining high information rates over limited numbers of information channels is becoming increasingly important in the checkout of complex spacecraft and military missile systems.

2.3 Example

A small scale example of a method of test point determination and the quantitative results in a simple two-stage transistor amplifier assumed to be a part of a larger subsystem are shown in Figure 5 and Table II. The process is a very detailed one and leans heavily upon an intimate knowledge of the circuit. The test point selection cannot really be independent of the rest of the system. For this example, however, it is assumed that the circuit represents a black box with signal inputs and outputs and with power from a separate power supply. To be typical, test point X (Figure 5), is therefore assumed to be elsewhere in the system, representing "free data", but test point H (the B + lead) is assumed to be a part of this box.

Test Point Isolation

For simplicity, series isolation resistors are not shown in the example, although they would normally be present. In most cases, particularly where only d-c voltages are to be measured, there are no serious restrictions to the insertion of a series resistor whose value is high enough to eliminate any effect upon the circuit from a test wire short or ground. Usually, the test measurements can be made with the required accuracy through the resistor. Where this is not true, as in low impedance or very low level measurements, there are usually several possible solutions, based upon compromises, trade-offs, or use of other points. Capacitive or inductive coupling may also be employed along with data conversion devices such as two resistor voltage dividers, diode rectifiers, and others to simplify the interface between the prime system and the checkout equipment. If the relative failure mode detectability is very small the test point can be omitted altogether. If the failure rate of the tested failure modes at the point in question is high compared to the failure rate of the test wire and assuming there is no other way to assess it, the test point can be wired in without isolations, using maximum reliability techniques.

Selection Procedure

In practice, the probable value of certain test points, such as A, D, E, and F (Figure 5), is obvious on inspection, and they are selected on a trial basis until their value can be estimated quantitatively[1].

Having made one or more trial selections of test points considering also test data which is available "free" from elsewhere in the system, all circuit parts and their appropriate failure rates are listed. Also listed are the ways in which each can fail. A part is considered to have failed when any principal characteristic reaches some limit which the designer has established as indicative of an inherent abnormality[6]. An example would be the case of a wirewound resistor used for reliability, normally 2%, which measures 10% high. The exact nature of the abnormality may not be known, but the probability of future failure seems unacceptably high, and the trouble should be cleared.

Opposite each failure mode should be listed its estimated relative frequency of occurrence which is then converted to a partial failure rate of the part. This is an intricate process involving some abstract estimates, partly because of the present state of the reliability art, but a skilled designer will find that with some practice he can do it rationally. He must remember that different circuit uses of a part make different failure modes more likely. He must also take account of the fact that some appreciable fraction of the time he will discover a failure symptom before a failure actually occurs. Existing parts failure rate data is sufficient to provide strong guidelines, and an experienced designer can adjust it to make these detailed estimates.

The next step is to match measurements and tests to the parts failure modes using the tentative lists of test points. Parameters and characteristics are checked with sufficient accuracy to determine whether a failure condition exists. It will be found that there is not a one-to-one correspondence between measurements and possible failure modes. It is clear, for example, that a power-off impedance measurement will, in many cases, have to consider parallel paths in the circuit, although evidence is gained that associated capacitors have proper isolation resistance.

Proceeding in this way, it will be found that many potential failure modes can be checked completely with a given set of test points. Others have only a probability of detection, (which is taken into account), while some cannot be detected at all.

When this process is complete, the rates associated with the assessable failure modes can be determined from the lists and summed. This sum, divided by the total failure rate, provides a measure of the testability of the circuit with the particular set of test points. The assessable failure modes subtracted from the total failure mode-rate gives the undetectable potential failure rate.

Sample Results

This analysis has been performed for transistor circuit of Figure 5, using three levels of testability.

In considering the results in Table II, there are additional aspects of this analysis that must be brought out. First, it must be assumed that each circuit is housed in its own module or black box, and that there are sources of failure other than the detailed parts failure modes discussed above. In particular, there may be electrical failures such as oscillation, interaction with other boxes, and noise generation or pick-up, internally or externally caused.

TABLE II

BASIC DATA	TRANSISTOR AMPLIFIER
Number of Electrical Parts	18
Failure Rate: Electrical Parts	1.1 per cent/hours
Failure Rate: Mechanical Shorts, Presence of Foreign Objects, Etc.	2.0 per cent
Total "Black Box" Failure Rate	3.1 per cent
MTBF (Assumes new equipment ∉ no test)	32,000 hours
End-To-End Test (3 Test Points)	
Per cent of Total Failure Modes/Rate Checked	51 per cent
Per cent Undetectable Failure Modes/Rate	49 per cent
MTBF (Based on Undetectable Failure Modes)	67,000 hours
Intermediate Quality Test	(4 test points)
Per cent of Total Failure Modes/Rate Checked	56 per cent
Per cent Undetectable Failure Modes/Rate	44 per cent
MTBF	74,000 hours
Most Complete Test	(9 test points)
Per cent of Total Failure Modes/Rate Checked	60 per cent
Per cent Undetectable Failure Modes/Rate	40 per cent
MTBF	81,000 hours

There is also a long and important list of "mechanical" possibilities which include such things as shorts caused by loose pieces of solder or other foreign objects, abraded wires, loose parts, poor connections, etc. While difficult to deal with quantitatively, failures whose causes fall into the misuse category cannot be neglected. Internal box temperatures is a measurement which checks one common failure-producing stress level. The resistance of a copper wire winding is often enough to provide an adequate temperature reading.

The electrical sources of failure not traceable to a part may be handled by an analysis including several boxes, each being considered as a component of the larger subsystem, and measurements made to guard against this kind of failure assuming the measurements were not already called out at parts level.

Depending upon the kind of failure and the general situation, an additional failure rate might be assigned to these additional possible failure modes. Alternatively, it could be decided that the measurements for oscillation, noise, temperature, etc., are only additional insurance against failures whose rate has already been included. This was the decision for these examples.

The probability of failure due to "mechanical" shorts, etc., is handled by assuming that there is a quantitative failure rate applicable to these failures as a class. Assuming also good quality control and visual inspection, this has been estimated as 2% per 1000 hours. It has been further assumed that the probability-of-detection in the more complete test is 50%. That is, it is about as likely that the trouble will first be detected during a test where it can be corrected without an operating failure as in the form of mode failure during a mission. This estimate would vary greatly with the kind of system and its operating profile.

In a particular situation it will be found that certain failure rates are controlling. In a vacuum tube circuit, for example, the tube failure rates are generally high and often equivalent to that of all other circuit parts together. The transistor circuit presents a different picture. Here the transistor failure rate is not much larger than that of the other individual parts. The contributions to total failure rate of the "box" are from two main groups: all the electrical parts, and the group of miscellaneous "mechanical" failures.

The absolute results in Table II are not as significant as the relative results. These show clearly that there are substantial improvements possible by improving the quality of the test to permit timely replacements of dubious parts. The improvement per additional test point is dependent upon the way the failure rate is distributed. The mean-time-between failures (MTBF) in the case of the example transistor amplifier increases from 67,000 hours produced by a more or less conventional test program to 81,000 if ten test points are used.

The economic value of such improvements for a system can be estimated theoretically by calculating how many redundant units would have to be purchased to achieve the same affect. A good test regime, however, has equally important effects upon the availability of the system or systems, skill levels and numbers of personnel, and repair efficiency, as well as another, longer term, effect upon reliability growth, all of which must also be taken into account[7].

The precision of available failure rate data and the state of knowledge of failure mode relationships is open to question in some cases, but the ability to secure better failure data by employing probing tests in the vicinity of the possible failures seem well established.

Broadly, this approach to system design-for-testability and the related test data handling concepts differs from today's typical test approach to these respects:

- o More detailed testing of internal performance - more test points - more data.
- o Better evaluation of the test data by means of logical equipment able to distinguish between normal and abnormal conditions, and to handle one set of test data as a function of the content of another.
- o Emphasis on application of environmental or operating stress conditions, during tests.
- o The entire test regime is governed and evaluated by quantitative methods and standards, all related to equipment reliability.

2.4 Fault Detection Requirements

The capability of the checkout equipment to detect faults answers the question: "Are there evidences of present malfunction or faults?" As has been pointed out, each test situation has in it a category of faults which cannot be detected, termed "Undetectable potential failures or invisible risks." The size of the category determines the probability of fault detection and is an inverse function of the amount of fault data available and the efficiency of the automatic checkout equipment using it. It is necessary, therefore, to maximize the failure information content of the test data rather than to reconfirm abstract design parameters. One technique employed for this achievement is called "inferential or introspective testing" which, complemented by end-to-end testing, is especially powerful in testing closed loop systems. Another approach and technique is that of wringing all possible test data from a fixed set of test points by "network testing." The point to be made here is that a good test approach really involves several complimentary techniques, all related by a unified set of objectives.

Nevertheless all failures are not predictable by an ACOE even when combined with outstanding design for testability. This is either because the harbinger of failure is not located in the equipment or because, while present, it is not in a form for measurement. The precursor of a failure due to excess environment stress, for example, is inherently not present, while a manufacturing flaw in the paper dielectric of a capacitor is inherent but may not be detectable by any practical test[6].

There is a practical limit to failure resolving power and present test methods are not nearly as effective as they might be in culling out failures. The following seem to be the major reasons:

a. Too much dependence is made on end-to-end testing because of the belief that failures in essential parts are immediately and grossly visible on end-outputs.

b. The belief that there are intrinsically unpredictable or random failures, or that the class of failures which by practical means are unpredictable is much larger than it really is.

c. Failure to wring all results possible out of accepted sound test concepts such as marginal testing.

d. Lack of recognition that system design-for-testability is intimately related to the checkout equipment, and that only high-speed, random access ACOE can feasibly measure and assess the complex test data.

2.5 Fault Isolation

The question of "What is necessary to be done to eliminate the fault?" is more difficult to answer and often it is a case of localizing a fault to a functional area or assembly of units rather than isolation to a replaceable unit level. In most present systems only localization is possible when the word isolation is used. If it is claimed that a machine can fault isolate, it should provide conclusively, fault isolation -- not end up in a human trial and error activity.

Isolation, like detection, requires sufficient and appropriate data. As satisfactory fault detection with equipment designed for testability has required extensive data points, a relatively low percentage of additional points are required for fault isolation. As an automatic machine cannot think and analyze, it must be programmed with information in a repertoire of faults it recognizes with location data. Many common faults in electronics are not predictable in detail as to exact fault or its symptoms. Examples might include multiple malfunctions, noise pick-up, oscillation or instability, piece of loose solder, or intermittent connection. One solution to this impasse is to provide data at the part level plus attention to packaging interfaces at replaceable component level to get related functions in good logical relationship. Note that there is no fault isolation required if entire system is in one replaceable box. The fewer the quantity of units, the easier is fault isolation, so the effort to be applied to this area is inversely related to the functional size of the replacement unit.

Conclusive fault isolation to the replaceable component level in electronics subsystems requires that certain guidelines be established and implemented relative to the quantity of piece parts, and the manner in which circuit functions are packaged in the replaceable modules or components. These guidelines are needed because of the infinite number and variety of the failures and failure symptoms to which electronics is subject. It cannot be specifically predicted, for example, which circuits will be partially shorted by moisture, where a loose washer will land, or what combination of pins in a damaged loose connector will not make contact. For electronics systems, then, a logic chart for fault isolation is ultimately produced, which recognizes and helps define replaceable components and functional packaging.

2.6 Failure Prediction

One objective of design for testability is to provide the checkout equipment with capability to detect incipient or future failure in a system. The failure prediction requirements may be met, at least in part, through proper application of historical and statistical data, marginal testing procedures, checking failure sensitive parameters, and of comprehensive test

or inferential testing operations procedures.[8] The degree to which this approach will be effective in eliminating equipment failures during critical missions depends partly upon its ability to distinguish between a "normal" and an "abnormal" system. This in turn is a function of system design maturity which reaches its highest value in the operational phase. The design-for-testability can help the designer to distinguish between normal and abnormal deviations by providing for measurement of parameters such as temperature which normally causes drifts and by automatically separating such drifts from the total. The closer the test limits can practically be set to the tolerances on a given function, the greater the probability of finding a malfunction, but the tighter these tolerances, the greater the test equipment accuracy required. Calibrating out normal drifts, for example those caused by hot or cold operation, allows separation of abnormal malfunctions or drifts.

Until the design has become mature through measurement of deviations, environmental test, and flight test, however, the designer is not completely sure what constitutes normalcy nor does he know that a "normal" system surviving test conditions will also survive normal operational stresses. Hence, until a design is mature, an abnormality means a probable failure, but normal deviations do not mean certain success. Also related to equipment maturity, is the predictability and variability of environmental conditions. The extremes and the unknowns of a space environment make for problems in this area. The designer may do a perfect job of designing and establishing test norms against environmental conditions he is given, but these may be wrong and failures result, or economics may dictate that he knowingly design to less than maximum stresses, accepting the risk that peaks or worst conditions will not occur simultaneously. These risks cannot be reduced by testing. The effectiveness of failure prediction also depends upon total mission time. Symptoms of near-future failures probably are above the threshold of visibility if it is known where and how to look for them. Present symptoms of far distant future failures, however, may be lost in the general noise.

2.7 Application

The reference given in Part I of this paper regarding the ARINC program of tests employing similar techniques of testing to those described here is a good example of their application.[6]

As a second example, in 1957 a classic AF funded study of automatic checkout was made at Convair, San Diego, for the F-106 airplane. With the basic design established the study objective was to define and design a completely ACO system to verify the airplane system, to include conclusive fault isolation. The results supported these test techniques and, while specific and detailed for this weapon system, have general application. The resulting report, however, was classified and did not receive widespread circulation.[9]

3.0 AUTOMATIC CHECKOUT

3.1 Definition

In the present state-of-the-art it is not possible to define concisely automatic checkout equipment as distinct from semi-automatic and manual equipment. There are short definitions based upon the percentage of the

total test time an operator participates in or controls the test. One of these sets the limit between manual and semi-automatic equipment at less than 2 per cent operator participation and that between semi-automatic and automatic at 50 per cent[10]. It is preferrable to resolve the gray area between semi-automatic and automatic by applying these factors:

a. If it lacks either automatic test point selection, input device selection and conditioning, test programming, limit comparison, recording of results, or interpolated self-tests, it is not automatic. If it performs these functions, it may be automatic depending on the degree of the remaining factors.

b. Whether it possesses a basic storage, access, and logic capability sufficient to perform fault isolation, to adjust tolerances and make decisions as a function of other decisions and test results, and to scan an array of no-go's before taking a programmable action.

c. Whether it performs at least some of the functions substantially quicker or better than the operator, is useful to him, and is therefore an example of appropriate automation.

d. The degrees of self-test and risk of an undetected error.

The phrases "sequential program" and "internally stored program" are generally accepted. Although all known test programs are sequential in a sense, a sequentially programmed machine refers to one typically employing a set of punched cards, a magnetic tape, or a punched tape which provide all of the two classes of data to perform a test; that which programs and conditions the ACOE, and that which describes the normal performance of the prime system.

An internally programmed equipment refers to the case where a test program is stored in the form of a constantly accessible reservoir of data. It is not only the stored data which is constantly accessible, but the reservoir itself for the storage of partly processed data or data temporarily held for use with other tests. High-speed, random, variable dwell, input and output switching is also a requirement as contrasted with a slow or commutating switch. The program, therefore, is not fixed, but can change in ways determined by test results to which is applied a pattern of pre-set logic.

The above implies that internally programmed equipment is generally automatic if properly applied, while sequential or externally programmed equipment would generally be semi-automatic except in the case of very simple prime system problems.

In the fully automated checkout system, the human operators are replaced by a complex and quite capable machine, and the only manual operations required are to start the sequence and note the sequence completion. In ACO procedures, the following functions are controlled by a central automatic programmer rather than by a human operator:

a. Programming of the complete test sequence, prime and test equipment.

b. Synchronization and Timing of program functions

c. Stimulation, selection and levels

d. Signal routing commands and test point selection

e. Power application and control, prime and test equipment

f. Data processing

g. Output data value and limit comparison, tolerance level selection

h. Test result display and recording

i. Fault isolation sub-routines

j. Self-test process

3.2 Automatic Checkout Requirements

It is appropriate to examine the situation to see what the requirements and specifications for ideal ACOE might be. The factors which are of prime importance in the employment of ACO techniques may be listed:

a. Reduced test time

b. Reduced personnel skill levels required

c. Increased accuracy

d. Excellent repeatability

e. Central programmer for control efficiency

f. Thoroughness of test

g. Diagnostic testing techniques

h. Self-testing techniques

i. Reliability

j. Maintainability

k. Flexibility

l. Standardization

m. Economics

Test Time

ACOE is a "must" in testing complex systems in operational tests where time is of the essence. This also applies to much of the developmental and qualification testing required of modern aerospace systems.

Today's systems are large and complex and there is insufficient time to perform tests safely and accurately or to coordinate the results without mechanical assistance. ACO considerably reduces the time required to verify the prime equipment under test. One advantage of this is the reduction of flow and lead time on these equipments, resulting in higher production rates at the factory. It also means faster reaction times in the field for Military equipment, for example. The need for rapid pre-launch evaluation is obvious in the ICBM.

It can be shown theoretically, and confirmed in practice, that because of their size, complexity, and immaturity, our latest systems still have a high failure rate. This fact reduces the test time which can be tolerated to avoid aging but also requires better test techniques to increase the confidence level and actual mission reliability. Such test techniques are still farther out of the reach of non-automatic test procedures.

Ideally, there is no limit on the shortness of ACOE test program time, actually, the shorter the better. In order to provide this time requirement, the equipment must be inherently very rapid in operation. The test equipment speed must not be the limiting factor in a given test situation. The prime system will usually be tested dynamically and the test time should basically be limited by the unavoidable response time of the prime systems. The ideal ACOE model, however, can help in this situation by having the capability of testing several prime subsystems or making several checks on a given system dynamically, at essentially the same time.

The contributions made to ACO procedures by inherent equipment speed can be subdivided into two branches, the first of which covers the obvious advantages of being able to perform a test within a very short time. These advantages may be summarized as follows:

a. Wear and tear is reduced to a minimum which means that the test can be made more frequently if other advantages result.

b. Systems can be tested which have very short permissible running time and where a long test would be injurious or prohibitive.

c. The short test time means that delay of the test until some minimum time before use of the vehicle is possible, thereby reducing the chance of failure in the interim.

d. When the short test is performed just before launch, a combination of final checkout and actual launch control of spacecraft equipment is permitted.

e. Special high-speed measuring capabilities add up to a revealing test, and therefore, contribute to system reliability. In a good dynamic test the checkout equipment should be able to generate an input and almost simultaneously make several output measurements at different points to determine whether the response is proper.

The second branch involves measurements and functions which are only useful if they can be done in an infinitesimally small span of time, or they

cannot be tested at all. Examples of these might include the evaluation of a high-power transmitter with low heat sink capacity, in the search for an intermittent malfunction, or during system evaluation under conditions of an intense electromagnetic radiation pulse.

Skill Level

To perform a system test, even by orthodox methods, requires large numbers of personnel with high levels of skill. With this category of personnel in short supply, available skilled personnel should be freed of routine predictable tasks that can be performed better by a machine. Typically, a skilled technician spends far more time on non-technical and quite repetitive tasks such as programming test sequences, monitoring displays, and recording test results than he does in the technical decision-making for which he was trained at length. Application of automatic techniques relieves the highly skilled personnel for jobs which have not yet been automated and which require long years of experience and training to develop.

No matter how good checkout equipment may be, until personnel acquire confidence in it through experience, it is a psychological hazard. The ideal ACOE should, insofar as possible, provide a form of visibility as to its accuracy of operation. For one thing, conventional measuring and instrumentation equipment should be provided along with convenient monitor points so that interested personnel can verify any reading manually at the time of test. For another thing, the equipment displays should provide indication of how a test is progressing. In a high speed solid state machine, where there may be no outward indication that the equipment is working, visual or aural indications are required. Psychologically, the ideal checkout equipment must provide evidence to the operator that it is doing the job assigned. Manual over-ride provisions must be made.

Accuracy

A machine can be said to have an absolute kind of integrity and will objectively do what it is told and will perform to the accuracy to which it is designed. An overly conscientious human operator may tend to make errors under countdown pressures for example, holding a launch for truly trivial abnormalities when everything else is at maximum readiness, whereas an irresponsible operator will not only make errors, but will fail to recognize, to correct, or to report them. A machine is not inhibited by pressures, confusion, or the consequences of its actions, and will remember routine but important functions such as recording results accurately while performing its critical or urgent ones.

Machines can perform repetitive operations and give repeatable results at a much higher rate and with fewer errors than do human operators. A machine can maintain tighter and more accurate tolerances over longer periods of time. The very important error producing factors of boredom and frustration have not yet been observed in automatic checkout equipment.

Central Programming

Basic problems exist relative to communication between human operators performing a large system test, each man being an expert on a part of the test. Where there is a need to read, discuss, question, and verify details between each step of a manual sequential procedure, numerous opportunities for errors and misunderstandings exist, amplified by the pressure of the schedule and mission importance, along with an actual decentralization of command and control. In a fully automatic test regime all data is immediately available in one place for processing or display and efficient concurrent testing is natural. A common digital language permits several computers, or checkout equipments to communicate in full detail and act as a single unit. In a manned space or weapon system program this may include an on-board guidance computer or on-board maintenance unit and one or two ground control or checkout computers.

Diagnostic Testing Techniques

This subject has been considered in the preceeding paragraphs 2.4, 2.5 and 2.6. Flexible and extensive sub-routines in the program structure are required for the fault detection, isolation, and prediction tasks.

Information presented to the operator from a display panel, in explicit and simple terms, includes gross prime equipment status. The panel lights behind the appropriate indicators will light to indicate whether the prime equipment is launch ready or in one of the fault indicating conditions. In the case of a fault or a series of faults the status board would indicate in English terms, showing just what should be done for correction. The number of the faulty item is coded from a reference chart. In cases where information can be satisfactorily conveyed to the operator only by analog means, standard instrumentation equipment may be provided as an adjunct and the test program may be interrupted at an appropriate point for this analysis. The following are included: (See Figure 6)

a. System GO/NO-GO information
b. Identification of unit under test
c. Identification of test under way
d. Test status and time count information
e. Unit under test information and status
f. Launch complex information

Checkout Equipment Self-Test

An important part of a checkout system is the verification of its own internal operation. This verification may be accomplished in several different degrees, from a very cursory check to a relatively complete evaluation. The incorporation of self-test features into ACOE is a controverisal subject; while it appears that self-test would greatly enhance the confidence factor in the prime equipment, this is not always the case. The inclusion of self-test

features frequently introduces additional complexity into the checkout equipment wherein the reliability of the over-all system may actually be reduced. It may result in 20% to 60% increase in physical quantity of logic equipment.

It is generally recognized that whenever a fault is indicated during a test sequence, it is first the test which is at fault, especially true with highly automated checkout equipment. One of the largest jobs of self-check capability is, therefore, to get around pre-conceived ideas of test equipment tendencies toward continuous malfunction. Three steps may be taken to assist the automatic checkout equipment designer in this area:

a. Through the employment of high speed, internally programmed checkout equipment, self-test routines may be made as often as desired, preferably several times during the short test duration.

b. At the time of an indication of fault in the equipment under test the quantitative value of the malfunctioning test parameter should be displayed prominently and automatically along with the correct parameter reference value and tolerance limits.

c. As a psychological and test aid, an accessible test point matrix should be provided in the advanced ACOE where instrumentation equipment may be used to make manual checks on each of the parameters tested by the checkout equipment during a manual program mode of operation.

The feature of static tests without time penalty is the characteristic that permits practically fool-proof ACOE self-test routines to be used to guarantee no test error. Many self-test techniques such as a parity check and sample problems are natural and commonplace in computer design. Others special to the test problem. such as an automatic challenge-and-confirm routine for all NO-GO's, can be programmed for confidence if there is no time penalty. The machine can be programmed to perform self-test routines during intervals it is waiting for system responses.

ACOE Reliability

The ACOE itself must be self-reliable. A checkout set which is subject to excessive downtime can seriously tie up the Aerospace vehicle program and waste the time of skilled personnel in maintenance activities. The definition of reliability of a test equipment of any kind includes not only the probability that it will perform properly when needed, but also the probability that it will not reject a good vehicle or pass one that is malfunctioning. Actual increases in the exhibited reliability of ACOE has been achieved since the employment of mature solid-state digital equipment.

The standard techniques for maximizing reliability which are used in prime equipment design also apply to design of checkout equipment, manual or automatic. Foremost among these are the following:

(1) Design simplicity including a minimization of the number of components and component complexity for a given circuit function.

(2) Component de-rating. High reliability can be obtained through the use of components whose operating conditions in the equipment are well within their ratings for power, temperature, voltage, humidity, and tolerances on their basic electrical characteristics.

(3) Redundancy in circuit components when this is established to be required.

Maintainability

Related to reliability is maintainability. An ideal equipment should not break down, but if it does, it should be easy to put back on the line in minimum time.

The inevitability of less than 100% reliability of any equipment ultimately necessitates its repair and maintenance. Also, in systems of high complexity, certain adjustments are required in order to optimize over-all performance. Thus, a vital consideration in the design of components of a system, whether it be spacecraft or checkout equipment, is to provide the facility for rapid and easy adjustment, repair, and replacement.

Flexibility

A major characteristic of any large intricate system is change and modification. The ideal ACOE must be versatile and sufficiently flexible in capability so that it can be designed before every parameter and tolerance limit of the Aerospace systems it is to test can be specified. It should also be sufficiently flexible so that it can be quickly reprogrammed to test another system and with spare capacity so that it does not become obsolete with respect to the next generation of Aerospace vehicles. It should be special only in the sense of the special program needed for a given test. Through the measurement of fundamental electrical parameters, basically the same ACOE may be used on several spacecraft programs of limited quantity procurement without complete redesign of the equipment. The high versatility tends to eliminate adapters special to a given prime system, and the ACOE does not grow obsolete with a given prime, but is reprogrammed and assigned to another, or for use during equipment design phases, and environmental and acceptance testing at the lower test levels.

Standardization

In ACOE it is a necessity that components, modules, sub-systems, and systems, as well as in the procedures for use of this checkout equipment, be standardized as far as practicable. Standardized circuit elements are generally employed at the current time, with replaceable modules as the fundamental unit. One basic module is a printed circuit card which plugs into a standard chassis or unit file. These units are combined in electronic equipment cabinet racks in such a way that they are easily replaced or modified. In this way felxibility is enhanced, repairs are expedited, and cost is minimized.

Economics

Some of the rather large benefits that accrue from this systems approach to ACOE are supported by the economics of the situation and can be measured in dollars on a fairly consistent and objective basis. This is in addition to any advantage in value of flight safety and national prestige (of over-riding importance in many types of missions) which do not lend themselves to quantitative evaluation. These benefits basically arise in the following four ways:

a. This type of equipment is basically an automated programmed multiple tester with a high-speed measurement capability having full access to all of the parameters it is supposed to measure. Its design is such that in testing a very large system all of its parts are used over and over again at high speed. So, beyond a certain point, except for input capability and memory capacity, the size and cost is not a linear function of prime system size or program complexity. (See Figure 7.) At first, as the task is increased it is found that both the capacity and the measurement, logical, and other capabilities of the ACOE are increasing, so the cost curve rises more or less linearly. Later, when a sufficiently broad spectrum of tasks has been covered, the ACOE contains "all necessary" capabilities. Further increases in the test task requires only larger capacity, so the cost curve flattens out. Some studies have indicated that an efficient machine should have available three to five thousand input test points which can also be used as stimulus points. Memory requirements are in the range of one to three million bits.

b. By the increase in the availability and reliability of a given system, an improvement convertible directly into dollars as previously discussed in the Part II material of this paper.[1]

c. In the area of technically skilled personnel by decreasing both the skill levels and numbers required, and by taking routine functions off their hands as brought out in the previous paragraphs.

d. As a test regime is improved in certain basic respects, there occurs a compounding of inter-related cost savings in the improvements. The Convair study[9], which considers the lower order terms and some of the higher ones offers evidence that if, for example, we were talking about a system whose reliability and availability were of the order of 60%, and if these were then increased by a factor of 1.25 (25%), the improved effectiveness could only be matched by purchasing an equal number of additional systems. In making the quantitative cost trades involved in establishing a test philosophy, other cost savings are compounded through less tangible items such as inventory of spares, production tooling, quantity and quality of personnel required, training time required, etc.

Maximum use design is an important factor in economics, that is, the utilization of similar checkout equipment at several levels of test. Under this concept the system checkout equipment, or at least a portion of it, is designed for use at lower level testing as well as at the integrated system level. As a result, minimum equipment is required to meet evaluation needs for all test levels and integrity of testing from unit to the missile or spacecraft system or integrated system level is maintained.

In the past, in general, for the one-of-a-kind space probe launches, it has been generally more expedient to use highly trained personnel than to expend time and money during a compressed schedule for the design of highly sophisticated system checkout and launch control equipment. Utilizing the new techniques in application of high-speed computer type programming along with prime equipment design for testability, however, is expected to reverse these previous decisions.

3.3 Internally Programmed Machines

The digital computer has become popular because its capability in the fields of computing, control, and logic is orders of magnitude beyond previous data handling methods. This capability is based primarily upon its high speed which enables it to perform complicated and extensive tasks rapidly in simple steps, and to its rapid access to large quantities of internal and external data it can manipulate.

If we add to this the measurement capability of a modern high-speed analog-to-digital converter and an electronic commutator for selecting test points and stimulus inputs, such a data processor or ACOE can have the same desirable impact upon our ability to determine by test, the true condition of a complex prime equipment system. This technique in ACOE will permit evaluation of all critical spacecraft functions at the last moment with GO/NO-GO information presented rather than the checking of a few of the most critical functions through the gathering, calibrating, interpreting, and checking of telemetered data as in current methods.

One of the most serious technical problems in the ACOE field today is the lack of understanding of the completely different kind and degree of capability possessed by a high-speed, internally-programmed digital ACOE as compared with a sequentially-programmed comparator. Properly integrated with a complex prime system, computer-like checkout devices will probably soon have the same impact on the maintenance and the mission reliability of high performance systems that the digital computers have had on data processing tasks.

A second problem is the conventional handling of the interface between the prime system and the ACOE. The present approach is to provide complex "analog" adapter units at the interface, the ACOE acting merely as a programmer-comparator. This approach leads one to decide, with some justification, that the adapters are merely a new, expensive form of the special manual test equipment of "pre-automation" days and that another tier of complexity has been added with little benefit, but with the usual maintenance and economic penalties. It is believed that with the proper design provisions in a prime system, internally programmed ACOE equipped with a high-speed analog-to-digital converter, a fast random switch and other programmable input/output devices and together with a well rounded command capability, the need for special adapters or interface equipment is minimized.

Capabilities of Internally-Programmed Machines

Internally programmed ACOE of the magnetic drum, disk, or core type has entirely different, and in some ways much higher, test capabilities than either a sequentially programmed machine or a human operator. An automatic machine, however, does not have the power to analyze, so the special test techniques which have been described are required to permit these inherent capabilities to be fully utilized. In addition to meeting most of the ACOE requirements stated in Paragraph 3.2, this type of equipment has the following notable specific characteristics:

a. High Speed Operation

Divided into two kinds of capabilities, the first is the time for a single measurement, comparison or logical operation, which, taking only a few microseconds, is usually far faster than the maximum response of analog portions of the prime system. The second is the general processing speed consisting of a number of such operations and related data handling at such a speed (100 kc to about 1 mc, clock rate) that a long test can be completed in minutes, provided it is not interspersed with long system dynamic response delays, or, that only short dynamic responses are involved and that these, for the most part, can run concurrently.

b. Short Test Interspersal

The injection into a test program almost at will, those measurement sequences not delayed by system response time when they involve no appreciable test time penalty. A reasonably comprehensive "last minute" test of this kind can be run when otherwise there would be no time for a test at all. System changes which add requirements, repeat of crucial tests with results comparison, "static" test sequences as checking resistance or impedance of all test points to ground before applying power, and a check of all system static parameters for signs of trouble before starting the time-consuming or equipment aging portions of the test program, are further examples. The work of R. Brachman and others at Frankford Arsenal has included this approach.[11]

c. Rapid Test of Radiating Systems

Under certain secure or busy conditions it is necessary to maintain radio and radar silence. A high-speed ACOE can be programmed to stimulate and test all radiating systems thoroughly in a matter of milliseconds.

d. Generation of Rapidly Changing Stimuli

The high-speed analog-to-digital converter working in reverse mode is capable of generating an accurate voltage level in from one to several microseconds and receiving the proper digital commands, it can generate almost any rapidly changing stimuli, including various wave shapes.

e. Signal Envelope Measurement

This is the capability which permits the equipment, by rapid point-by-point measurement, to determine whether a time-variant parameter stays within proper limits through some critical period.

f. Data Storage Efficiency

The data storage efficiency of a drum or core memory is extensive, far greater than that of a tape machine. Because many parallel identifable channels exist, each read from a different head simultaneously, the address material necessary to locate a particular group of data is far less than the data it calls out. A comparatively short address number can call out lengthy prime or sub-routines In any test program, many both short and lengthy routines are used over and over again in various parts of the test. In a random access machine, such routines are recorded only once and called out by a simple address each time needed. In a tape or other non-random machine these must be constantly repeated or the machine must be programmed to search back and forth continuously over the tape.

g. Instantaneous Branching

The capability involves an ability to branch or proceed to an alternate routine based upon a comparison of a measurement just made with the results of earlier measurements. Both the immediate branching which results from a fault detection, and the fact that earlier results are available for comparison is a characteristic of internal programming. Many other types of pre-set logic are possible through this capability.

h. Computation and Calibration

Certain computation and calibration operations require such things as rapid temporary storage for capabilities, for example, of narrowing test limits without increasing the risk of rejecting a good unit, by removing normal drifts from the test data, thus improving the resolution between normal and abnormal conditions.

i. Multiple Test Programs

Selective Skip: An internally programmed machine permits the automatic compilation of any number of special programs from the aggregate program. A number of "test buttons" can be provided each of which is capable, by simple programming, of calling out any measurement series including or skipping appropriate sequences. For example, one button or key might invoke all of the measurements for a complete test of the control system.

j. Reduction of Adapters

The need for so called adapters or equipment which is special to the prime system under test can be reduced without any fundamental limit due to the cumulative capabilities of the ACOE. Three of the techniques and capabilities instrumental in generating this trend are as follows: (1) Inferential Test Data - (Sometimes called "introspective") - Adapters, for example are frequently involved in measuring over-all outputs of systems such as transmitters and receivers or, conversely, in stimulating their inputs. By inferential testing techniques, it is basically possible to determine by inference that an equipment is providing a proper output by sufficient internal measurements without actually measuring that output. In practice, only partial dependence would be placed upon this principle. As a simple example, the measurement of a few parameters associated with a pulse magnetron may provide a better assurance that the magnetron is operating properly, and is a good risk, than any external measurement. These parameters might be the average current temperature, with warm-up time taken into consideration, heater current, heater voltage, and a measurement of the RF load as indicated by a d-c current from two diodes in the directional coupler (providing VSWR). Of course, these measurements also provide part of the data necessary to draw similar conclusions on other replaceable units such as the modulator, the antenna and the r-f plumbing. (2) Self-stimulus - Many sub-systems of course, receive their normal operating stimulus or input from an internal source. Employing an internally programmed machine, monitoring such inputs together with the measurement of the resulting outputs permits a simple rapid computation to be made to determine whether all of the outputs are proper, based upon the stimulus. (3) Signal Conditioning - The process of signal amplification, zero setting, normalizing, filtering, and rectification is provided by the standardized input equipment, electronically programmable to various modes and ranges through the high speed switch, with resultant efficiency of utilization.

An integrated systems checkout station of a research type is shown in Figure 8. This fully automatic checkout equipment employs a high-speed general purpose digital computer as its central programmer and its logic/decision element. The equipment shown consists of the computer, computer peripheral equipment, typewriter input/output, controls and display console, and auxiliary equipment including power supplies and detailed status displays. This research model is being set up to evaluate automatic testing techniques as described here and it has the capability to check out a major portion of the electrical functions in a relatively complex spacecraft system.

3.4 Disadvantages of ACOE

Most so-called disadvantages of ACOE are not really inherent in the nature of ACOE but are based upon misapplication or misunderstanding. Most of the common criticisms of ACOE are included in the following areas:

a. Increase in complexity
b. Self-inflicted maintenance problems
c. Inflexibility
d. Excessive cost
e. Training problem extension
f. Excessive data generation
g. Short test time not imperative
h. Extensive programming requirements
i. Increased downtime upon ACOE failure
j. Maintenance personnel skill level increase
k. Inadequate practical field experience with ACOE

The source of the criticism usually lies somewhere in ACOE history, and frequently involves an instance of:

a. A particular design of ACOE which is basically unsuited to its job such as sequentially programmed equipment required to perform sophisticated checkout and fault isolation on a large system.

b. Failure to allow for operator participation by providing for a spectrum of capabilities in the ACOE from manual to fully automatic for program changes, or for the operator to verify the accuracy of the measurements.

c. Expecting premature results - insufficient allowance made for equipment shakedown or operator training in initial phases.

d. No attention to test points or design-for-testability in the prime system.

e. Specific equipment unreliability, particularly of card-readers, stepping switches and relays.

3.5 Conclusion

Certainly payloads and space vehicles of the future will grow more complex and will incorporate completely new subsystems such as advanced inertial control devices, parabolic and oriented antenna arrays, and directional and command attitude control systems. Upper stage cryogenic systems, fluorine propulsion systems and the like will severely complicate automatic propellant loading problems on the ground. The checkout problem for nuclear propulsion systems will be considerable. This prime equipment will require increased efficiencies in new and elaborate checkout equipment. On the basis of experience to date, however, it is reasonably clear that the philosophy of simplicity, flexibility, and reliability while at the same time providing complete quantitative information on prime equipment status during system checkout of Aerospace programs will be continued.

Fundamentally then, ACO becomes a necessity when the system is large and complex, when time is short and well-defined, when the ultimate in performance and probability-of-mission-success are essential, when numbers of high-skill level personnel would otherwise be required for routine tasks, or when an unemotional, orderly, pre-established, standardized, centralized, checkout or countdown is of the essence.

The system approach to automatic checkout leads to the conclusion that it is required for large systems and that internally-programmed ACOE has the required capability. This conclusion is based upon the quantity and character of the routine measuring and data handling to be performed. Some of this arises from the need to investigate failure modes when and where they are detectable before they develop into mission failures for reasons and by techniques described.

The combination of these ACO requirements points to the internally programmed automatic checkout equipment employing computer design techniques as a natural medium to implement such a test program.

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LIST OF ILLUSTRATIONS

Figure	Illustrations
1.	Block Diagram, The Testing Discipline
2.	Checkout Equipment Basic Functional Loop
3.	Sketch, Types of Bonded Cable
4.	Sketch, Float Valve Instrumentation
5.	Two Stage Solid-State Amplifier with Test Points
6.	Advanced Automatic Display Panel
7.	Representative Cost of Automatic Checkout Equipment vs. System Complexity
8.	Research Model, Automatic Checkout Equipment

The Testing Discipline

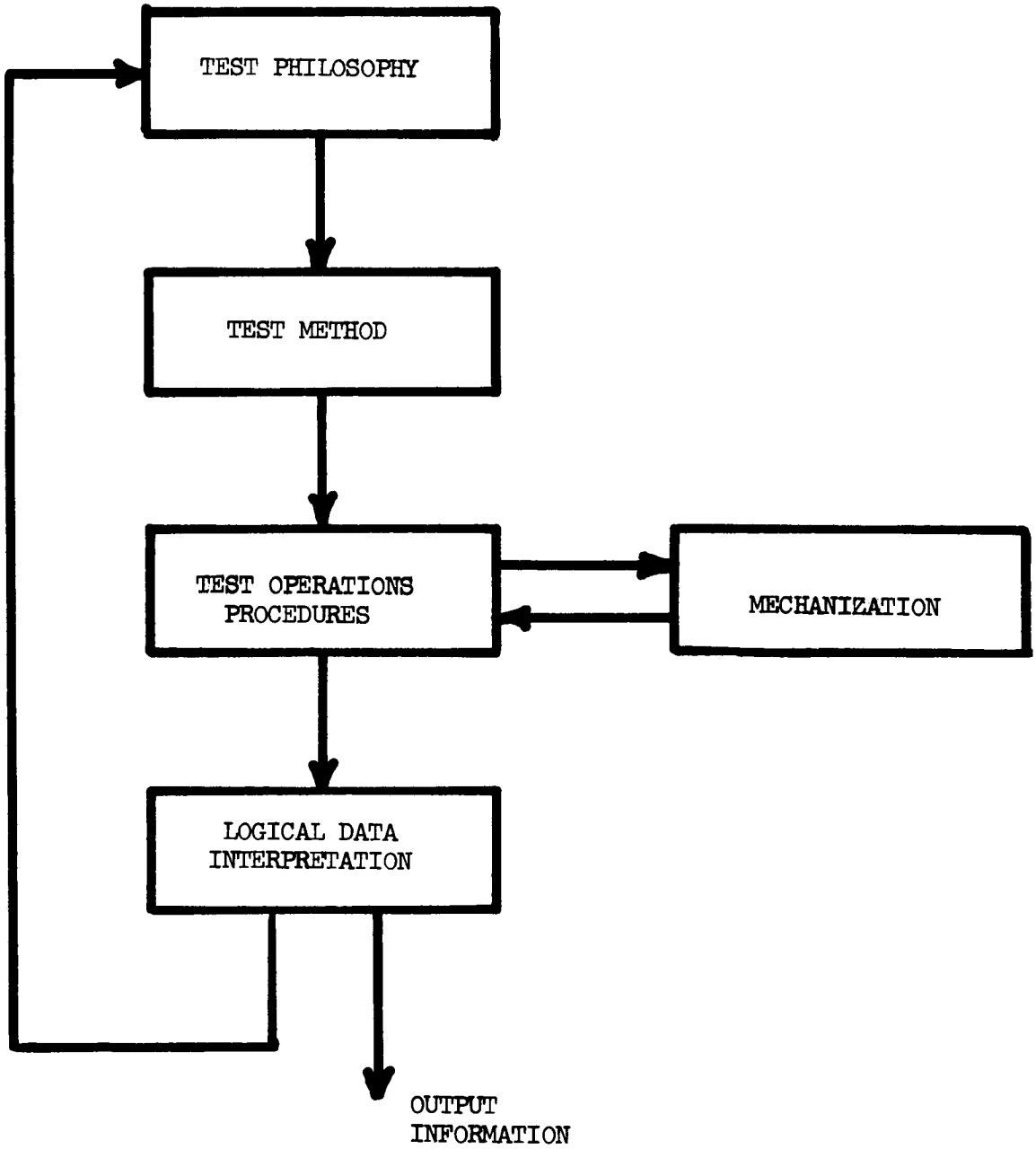


Figure 1.

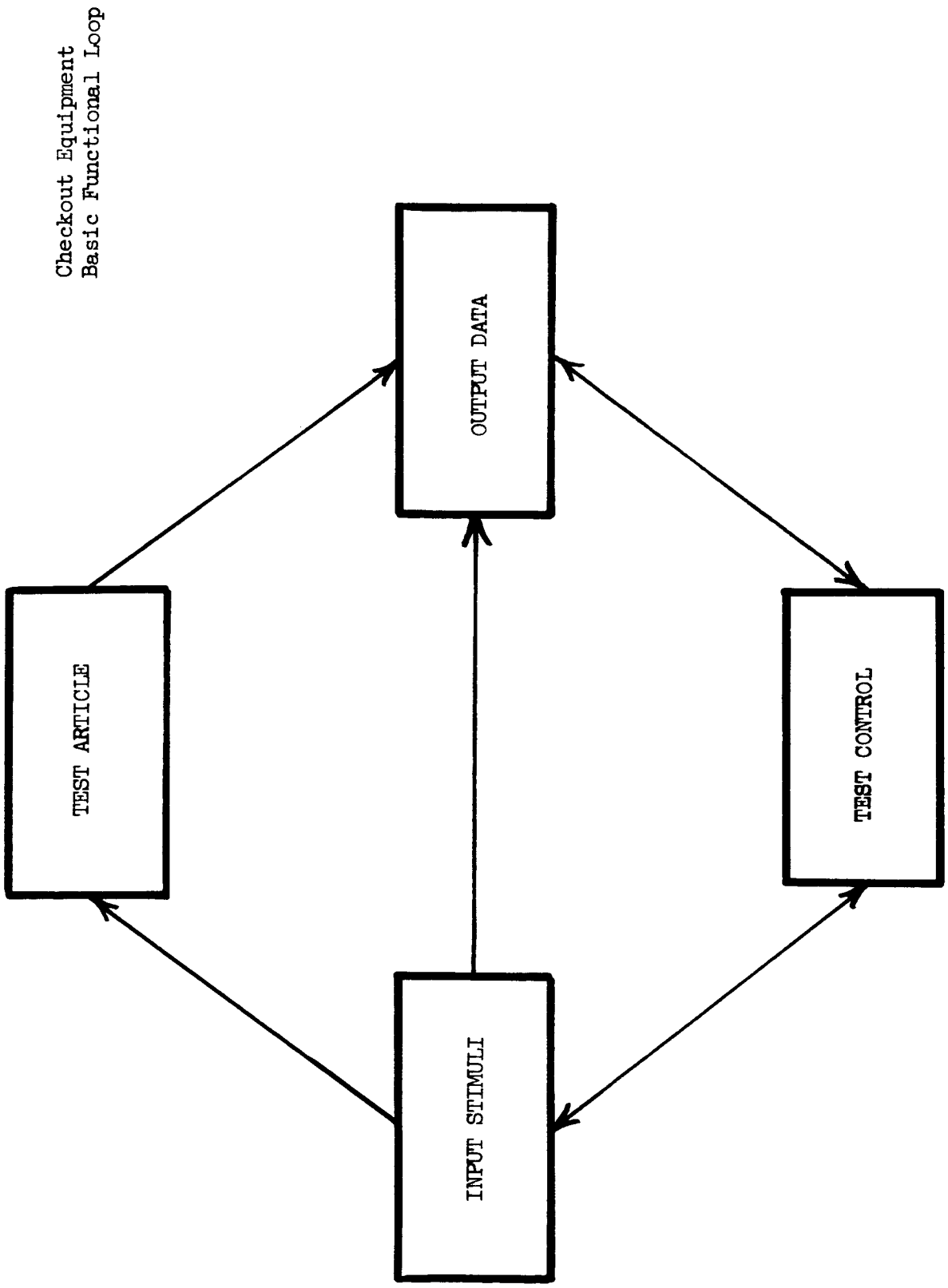
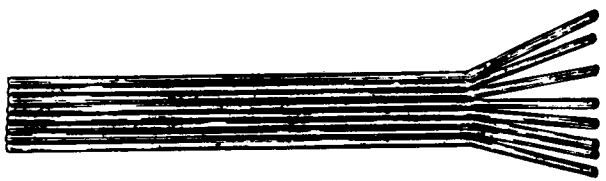

Checkout Equipment
Basic Functional Loop
OUTPUT DATA
TEST ARTICLE
TEST CONTROL
INPUT STIMULI

Figure 2.

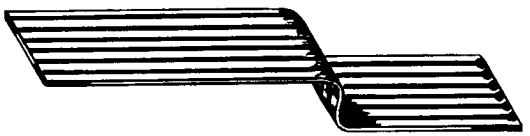
STANDARD AIRCRAFT WIRING
WT. FACTOR : 1.0



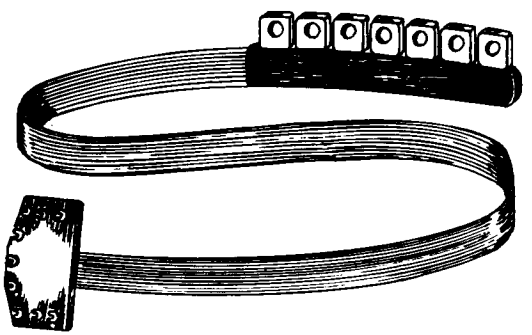
BONDED STRIP - TEFLON
WT. FACTOR : .47

BONDED STRIP - SILICONE
WT. FACTOR : .29

AVAILABLE TYPES
OF BONDED CABLE



PRINTED FLAT CABLE - KEL-F
WT. FACTOR : .33



PRINTED PIGTAIL - TEFLON
WT. FACTOR : .055

Figure 3.

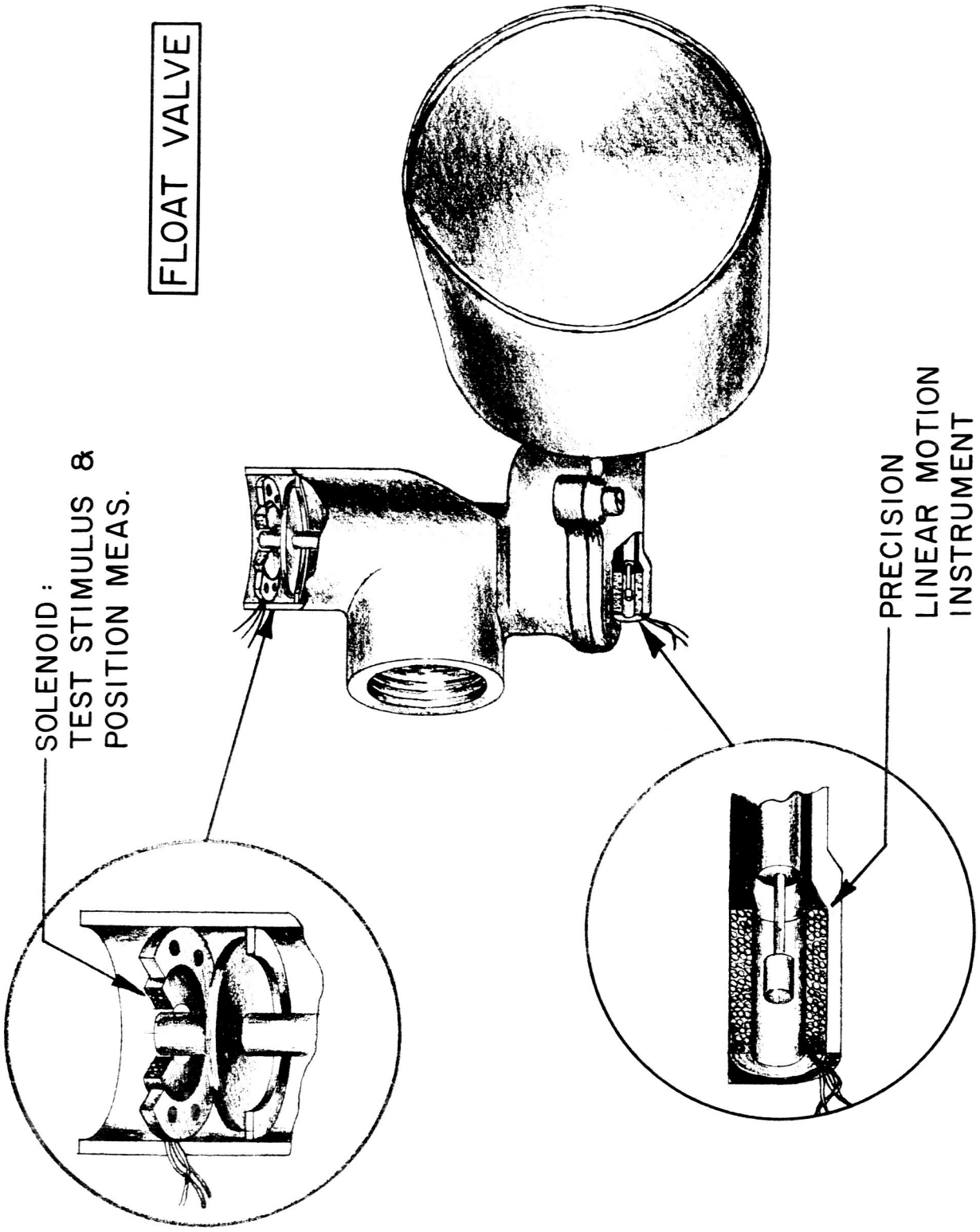
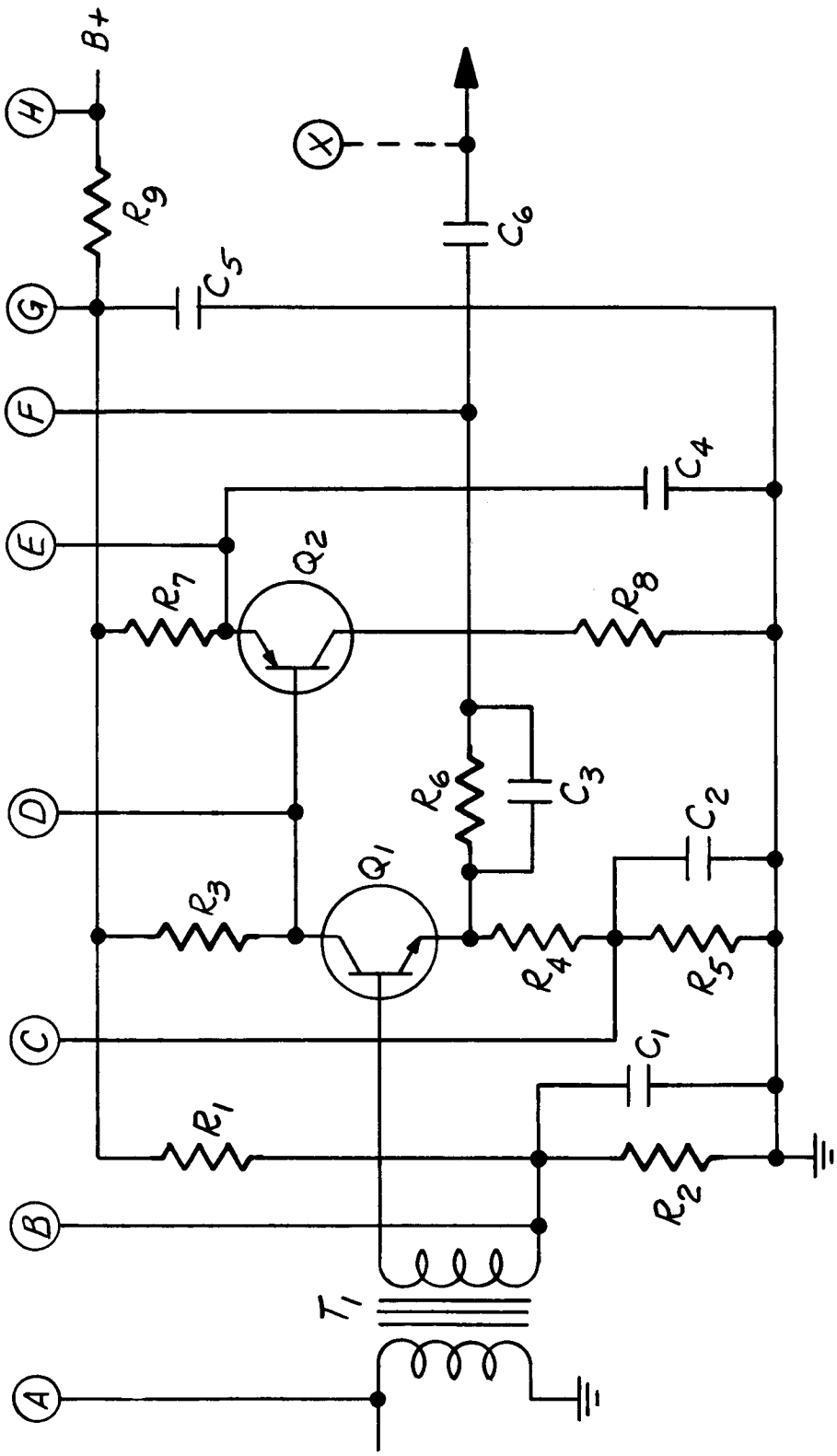

FLOAT VALVE
SOLENOID :
TEST STIMULUS &
POSITION MEAS.
PRECISION
LINEAR MOTION
INSTRUMENT

Figure 4.



TWO STAGE SOLID - STATE AMPLIFIER
SHOWING SAMPLE TEST POINTS

Figure 5.

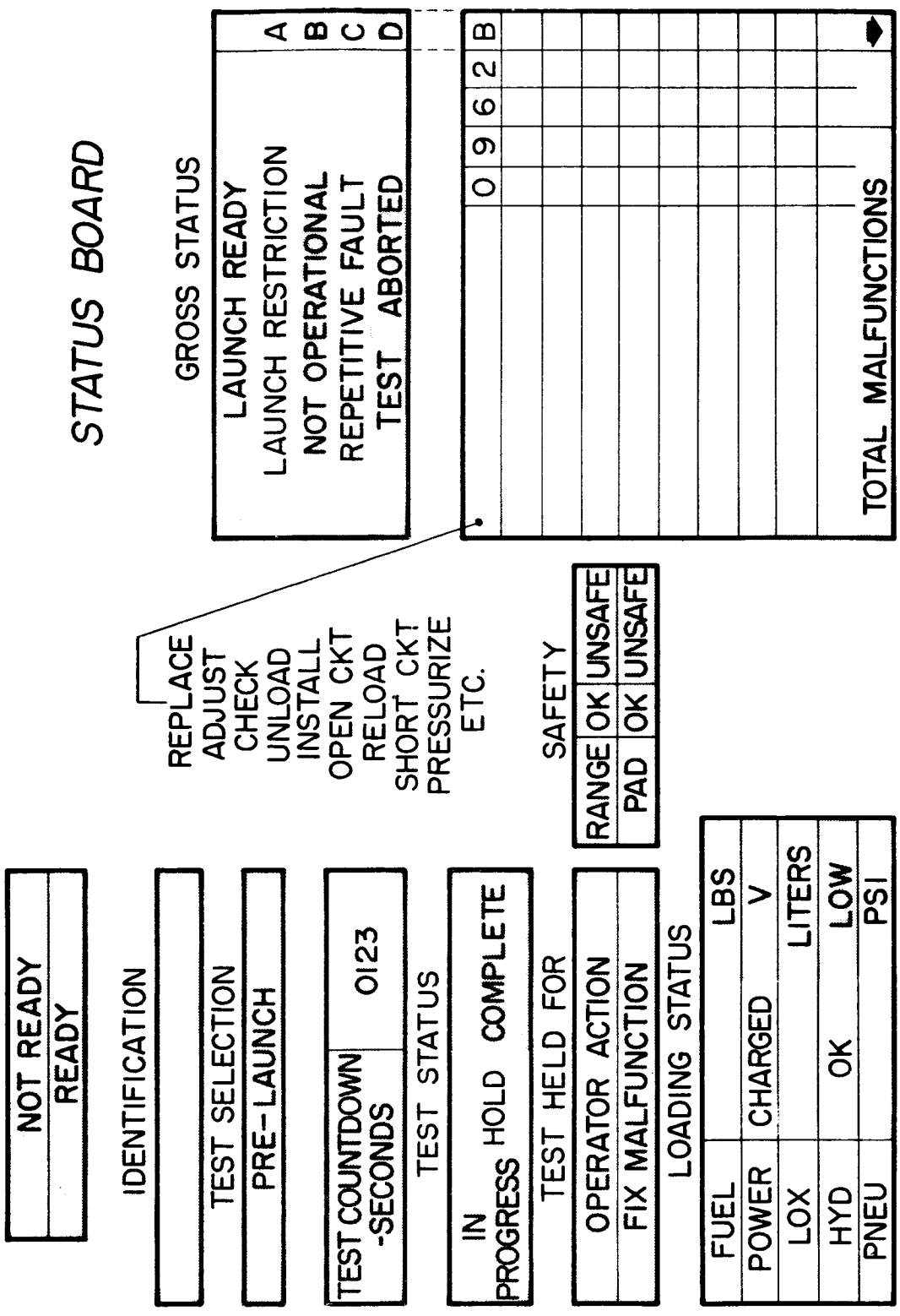

ADVANCED AUTOMATIC DISPLAY
STATUS BOARD
SPACECRAFT
NOT READY
READY
IDENTIFICATION
TEST SELECTION
PRE-LAUNCH
TEST COUNTDOWN -SECONDS
0123
TEST STATUS
IN PROGRESS
HOLD
COMPLETE
TEST HELD FOR
OPERATOR ACTION
FIX MALFUNCTION
LOADING STATUS
FUEL
LBS
POWER
CHARGED
V
LOX
LITERS
HYD
OK
LOW
PNEU
PSI
REPLACE
ADJUST
CHECK
UNLOAD
INSTALL
OPEN CKT
RELOAD
SHORT CKT
PRESSURIZE
ETC.
SAFETY
RANGE
OK
UNSAFE
PAD
OK
UNSAFE
GROSS STATUS
LAUNCH READY
LAUNCH RESTRICTION
NOT OPERATIONAL
REPETITIVE FAULT
TEST ABORTED
A
B
C
D
0
9
6
2
B
TOTAL MALFUNCTIONS

Figure 6.

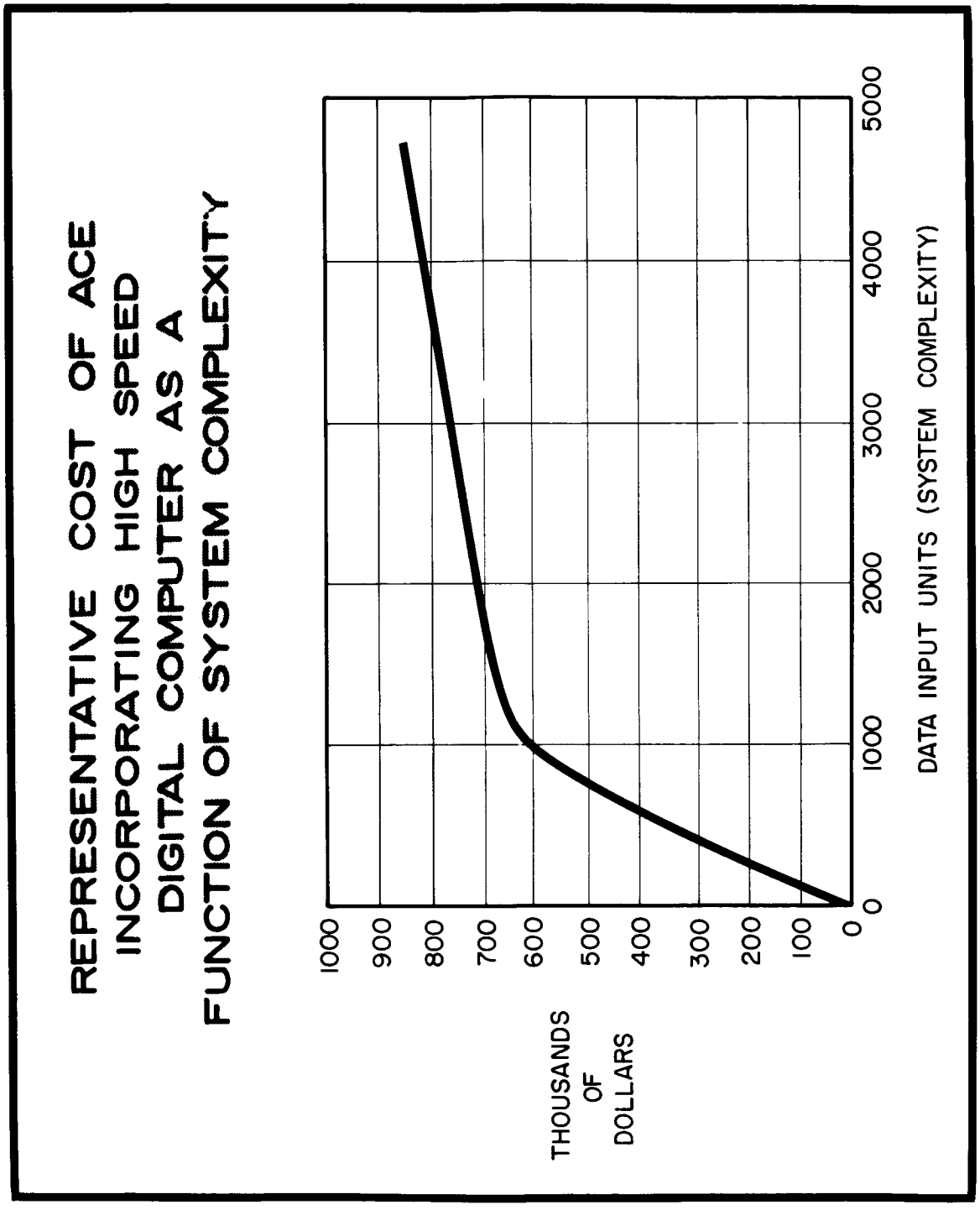

REPRESENTATIVE COST OF ACE
INCORPORATING HIGH SPEED
DIGITAL COMPUTER AS A
FUNCTION OF SYSTEM COMPLEXITY
THOUSANDS
OF
DOLLARS
1000
900
800
700
600
500
400
300
200
100
0
0
1000
2000
3000
4000
5000
DATA INPUT UNITS (SYSTEM COMPLEXITY)

Figure 7.

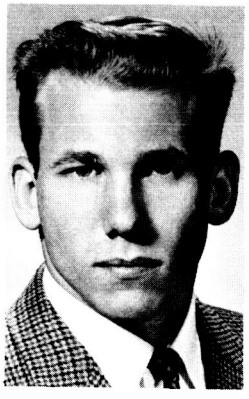
Figure 8.

PROJECT FIST: FAULT ISOLATION BY SEMI-AUTOMATIC TECHNIQUES

Gustave Shapiro and Owen B. Laug

GUSTAVE SHAPIRO, National Bureau of Standards.

Mr. Shapiro received his BSEE degree (George Washington University). He has been editor of the IRE Transactions on Component Parts since 1955; has served as a member of the National Administrative Committee of the Professional Group on Component Parts since 1952 and on the National Administrative Committee of the Professional Group on Microwave Theory and Techniques since 1957; has been on the Technical Program Committee and/or an organizer of sessions for the IRE International Convention since 1956; currently he is Chairman of the committee responsible for setting up the sessions covering component parts, production techniques, materials, and quality control for the 1964 IEEE International Convention. He is a Fellow of the Institute of Electrical and Electronics Engineers (formerly the Institute of Radio Engineers), and a Fellow of the Washington Academy of Sciences. Present position: Chief, Engineering Electronics Section.



OWEN B. LAUG, National Bureau of Standards.

Mr. Laug received a BSEE degree (University of Maryland). He is presently on the staff of the NBS graduate school. Mr. Laug has worked at the National Bureau of Standards 4 years, and is a member of the Institute of Electrical and Electronics Engineers. Present position: Project Engineer.

SUMMARY

PROJECT FIST: FAULT ISOLATION BY SEMI-AUTOMATIC TECHNIQUES

(A Paper in Two Parts)

by

Gustave Shapiro and Owen B. Laug
National Bureau of Standards
Washington, D. C.

Project FIST (Fault Isolation by Semi-automatic Techniques) has been conducted at the National Bureau of Standards under the sponsorship of the Department of the Navy, Bureau of Ships. Application of these techniques is biased toward shipboard installations and other areas where small size and weight, though important, are not overwhelmingly so, and where a moderate increase of size and weight may be profitably traded off against a practical maintenance capability. The system is one that must be included in the initial design of the prime equipment if its full potential is to be realized. To permit a better understanding of the role that this development might play in the future, it is appropriate to discuss its objectives and features.

(1) Emphasis has been placed on tests that will yield meaningful information, specifically dynamic tests that can measure the effectiveness with which the circuit under test performs the function for which it was designed.

(2) These dynamic tests are general in nature, equally applicable to high-power transmitting vacuum tube circuits or low-power transistorized circuits.

(3) Although the system has been devised chiefly for use by the untrained technician, who should not be required to make any decisions, it has also been designed so that the knowledgeable technician will not be prevented from using his initiative to improve the efficiency and effectiveness of the test system.

(4) The test set is a general-purpose, man-portable, semi-automatic instrument.

(5) Operation of the test instrument is very simple and uniform, regardless of the type of test being made. It is not necessary for the technician to have any knowledge of the circuit type being tested or the type of test being performed.

(6) Since there exist programing and test problem techniques that are peculiarly useful for diagnosing computer malfunctions, emphasis has been placed on techniques for diagnosing non-computer faults.

(7) The techniques are designed for fault isolation in modularized equipment so that the untrained technician can effect a rapid repair by replacing the defective assembly.

(8) Faults which the untrained technician cannot correct by replacing an assembly (such as defective interconnection wiring between assemblies) are not isolated by the test system. A trained technician should be called in to isolate and correct those faults that cannot be remedied by the simple action of replacing a module. It is the intent of this program to achieve the practical goal of minimizing the required number of trained technicians, not to seek the impossible goal of entirely eliminating the need for trained technicians.

(9) The techniques are capable of isolating defects in simple functional assemblies as well as in complex assemblies.

(10) Simple but efficient test-programing techniques have been developed to obviate the necessity for testing every module.

(11) The system seeks to make optimum use of the untrained technician to permit minimization of the test system complexity.

(12) The system has been designed for set-up and testing time under field conditions that is orders of magnitude shorter than the set-up and testing time required for conventional test equipment.

(13) Engineering decisions regarding the desirable types of tests and test tolerances required by a prime equipment are made in a laboratory atmosphere. Occasionally it will be found that cumulative field reports on the prime equipment will dis-

pute the wisdom of the original testing choices. It is practical to take remedial action in the field through the use of easily applied test modification kits.

(14) Since the human being is so constituted that he most effectively employs that to which he is favorably disposed, the system has been human-engineered to impart to the technician a ready understanding of its basic principles, a trust in its reliability, and an appreciation of its operating ease.

(15) The test set incorporates self-testing techniques which are readily comprehended by the untrained technician, thereby enhancing his confidence in the proper functioning of the test set when the self-test so indicates.

(16) The application of the testing techniques is relatively simple and will be codified in the form of a design manual so that the prime equipment design engineer can incorporate the fault location features in his equipment without requiring either the intervention or cooperation of the test equipment specialist. The intent here is to eliminate the interface problem that exists between the prime equipment designer and the automatic test equipment designer.

(17) The techniques advanced by the program are not of the "blue-sky" variety, but depend upon current state-of-the-art technology that is ready to be used here and now. Many of

the engineering hardware problems that might prevent successful application of the techniques have been investigated and practical engineering solutions to these design problems have been developed.

The FIST test set is a portable instrument occupying approximately one-fifth cubic foot. In the hands of untrained personnel it can perform a wide variety of meaningful dynamic tests at an estimated rate, including set-up time, of 600 tests per hour. The operator of this instrument need not be skilled in the use of test equipment because there are no controls to be manipulated, and the indication obtained requires that no interpretation or decision be made. He can locate the defective module rapidly and replace it without a knowledge of the function of the module or of the defect in it.

Test sockets and associated transformation networks form the interface between the prime equipment and the FIST test instrument. The test sockets are located on an easily accessible panel and are connected to the modules through passive transformation networks which convert the module parameter to be measured (amplification, frequency, waveform, etc.) to a voltage that is within the range of the test

instrument. The transformation networks are straight-forward and are easily incorporated into the prime equipment as a part of the original design.

Each test socket can accommodate a maximum of four tests, which is usually sufficient to determine whether module performance is within limits or not. The test sockets are arranged in an order which, if followed, permits the system to be tested efficiently (minimum time required to find the defective module), even though the operator of the test instrument is not familiar with the equipment being tested. The tests need not be made in any particular order, however, thus permitting a technician to deviate from the prescribed order when he so desires.

The success of Project FIST led to Project SAFARI (Semi-Automatic Failure Anticipation Recording Instrumentation) which will also be discussed. The SAFARI test instrument is similar to the FIST test set but incorporates a simple, effective means for recording the performance of the plug-in assemblies. Its purpose is to permit the operator to anticipate a failure and replace the module before the

failure occurs. It also provides a life-time performance record for each module, which information is useful for assessing the actual reliability experienced in the field.

PLACE -- PROGRAMMING LANGUAGE FOR AUTOMATIC CHECKOUT EQUIPMENT

B. H. Went and W. R. Irion

BURTON H. WENT, Battelle Memorial Institute.

Mr. Went received his BS degree (University of Portland). Before joining Battelle, Mr. Went worked with digital computers, designing and implementing an operating system for the FORTRAN compiler, and did some work on the SURGE data-processing compiler for the 704. Since joining Battelle, he has performed research to develop a problem-oriented language for automatic checkout equipment; has helped develop and implement a NELIAC compiler for the G-20; and was the project leader for Battelle's effort in the development of a COBOL system for the G-20. Mr. Went is a member of the Association for Computing Machinery and the Central Ohio Association for Computing Machinery. Present position: Project Leader, Automatic Checkout Programming Language.

WILLIAM R. IRION, Battelle Memorial Institute.

Mr. Irion received a BS degree (Capital University) and an MA degree (Ohio State University) with majors in mathematics. Active in the field of digital-computer programming since 1953, he specializes in the design and development of large-scale operating systems and problem-oriented languages and their compilers; he has worked on all the IBM machines from the CPC on, maintained the FORTRAN II and APT II operating systems, developed the SCATRAN for OSU 709/7090 Operating System, developed a source-language debugging system as part of the COBOL compiler-operating system for the Control Data G-20 and is presently working on PLACE. He is a member of the ACM and Central Ohio ACM. Present position: Senior Mathematician, Computation Center Group.

PLACE--Programming Language for Automatic Checkout Equipment*

by

B. H. Went and W. R. Irion
Battelle Memorial Institute

PLACE is a language for programming automatic checkout equipment that is controlled by punched cards, tape, a digital computer, or some other similar means. Some statements in the language have a meaning independent of the checkout machine being programmed whereas others depend on the machines for their meaning. PLACE has been applied to two checkout machines: one computer controlled and one controlled by a punched tape. Work will soon be started to prepare a translator for PLACE.

PLACE has the usual facilities of an algebraic programming language plus special facilities for checkout programming. The programmer may use suggestive English words to control the machine language programming. He may also write macros and subroutines in PLACE and then call for them in the program.

The tutorial will be conducted in two sections. The first will describe the use of PLACE with the AN/GJQ-9 and the second will cover some of the novel features of the language and its translator.

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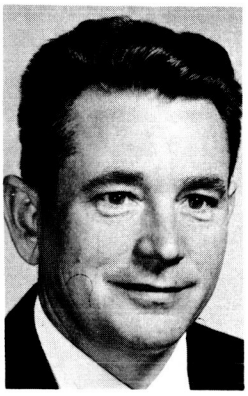
* This is a summary. A report will be published during the next year.

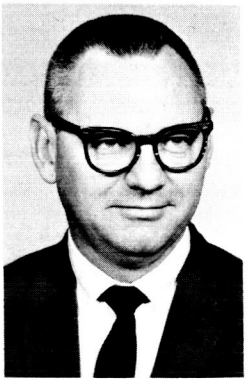
THE ROLE OF ELECTRICAL SYSTEMS IN THE SATURN CAPE OPERATIONS

R. M. Aden, E. T. Baggs, and G. P. Barr



ROBERT M. ADEN, NASA-Marshall Space Flight Center.

Mr. Aden received a BSEE degree (Mississippi State University) and has been connected with electrical communications since 1949. He joined Redstone Arsenal in 1951 and transferred to NASA in 1960. Present position: Chief, Systems Operations Design Branch.



ELLIS T. BAGGS, NASA-Marshall Space Flight Center.

Mr. Baggs received a BSEE degree (Vanderbilt) and started his work in the computer field with IBM although his electronic experience dates back to World War II. He was with Redstone Arsenal from 1954 to 1960, when he transferred to NASA. Present position: Deputy Branch Chief, Systems Operations Equipment.

GLENN P. BARR, George C. Marshall Space Flight Center.

Mr. Barr received a BS degree in Electrical Engineering (Michigan College of Mining and Technology). He joined the development team now associated with Marshall Space Flight Center in 1957 and has been active in the development of Ground Support Equipment since that date. He has participated in the team's numerous programs as a Project Engineer and is now responsible for automatic checkout techniques. Present position: Project Engineer, Systems Operation Equipment Design Branch.

THE ROLE OF ELECTRICAL SYSTEMS IN THE SATURN CAPE OPERATIONS

R. M. Aden, Chief
E. T. Baggs, Deputy Chief
G. P. Barr, Technical Assistant

Systems Operations Equipment Design Branch
Astrionics Laboratory
Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

The history and future trends, including detailed functions, of the equipment required to automatically checkout the Saturn vehicle at Cape Canaveral are discussed. The history gives an insight into the events leading up to the present design philosophy. The various functions of electrical systems are described to show their role in augmenting the launch checkout and operation. This paper deals primarily with the electrical systems requirements external to the operational computer system. Likely trends for future systems and types of equipment dictated by these trends are briefly discussed.

The cooperation and assistance of the various branches of Astrionics Laboratory, MSFC, and in particular the Systems Operations Equipment Design Branch in preparing this paper are gratefully acknowledged.

INTRODUCTION

History

Through the years, from the early rockets at Peenemunde to present day space age, launch vehicle checkout philosophies

have experienced continuing design evolutions. This evolution has demanded and resulted in steady technological advances throughout the many defense and space programs for which our design engineers at Marshall Space Flight Center have been responsible.

These programs began with Operation Backfire in England, Operation Bumber at White Sands, followed by the Hermes, Redstone, Jupiter, Jupiter C, Mercury Redstone, Pershing, and the Saturn program which is now well underway at Huntsville and throughout the nation.

Design Philosophy

Originally, the electrical system consisted of a number of upright cabinets into which were placed panels and chassis so designed and arranged to perform a particular function. Little standardization was attempted; therefore, each change to the electrical support equipment (ESE), necessitated by changes to the vehicle system, required extensive rework and rewiring to route signals, power, and data correctly. At the same time, all controls for checkout were manually operated by various station operators, and it was not until the "preparation complete" signal lamp came on and the launch sequencer took over that the system went into an automatic mode. Through ignition and liftoff, everything was automatically sequenced by a timer operating through diode logic and relay switching to control the various necessary events.

Hardware Standardization

The first significant step forward was that all connections for the switching and logic functions were terminated in patchboards. A checkout system could then be built well in advance of finalization of the launch vehicle's systems completion with a high degree of confidence that any changes required could be accomplished at the patchboard. Furthermore, by bringing each point to a test panel, it is possible to easily test a system and monitor for signals or faults.

Another advantage of the patchboard programmable technique was the use of standard modules for the patchboards, relays, diodes, control panels, and the standardization of rack sizes (Fig. 1).

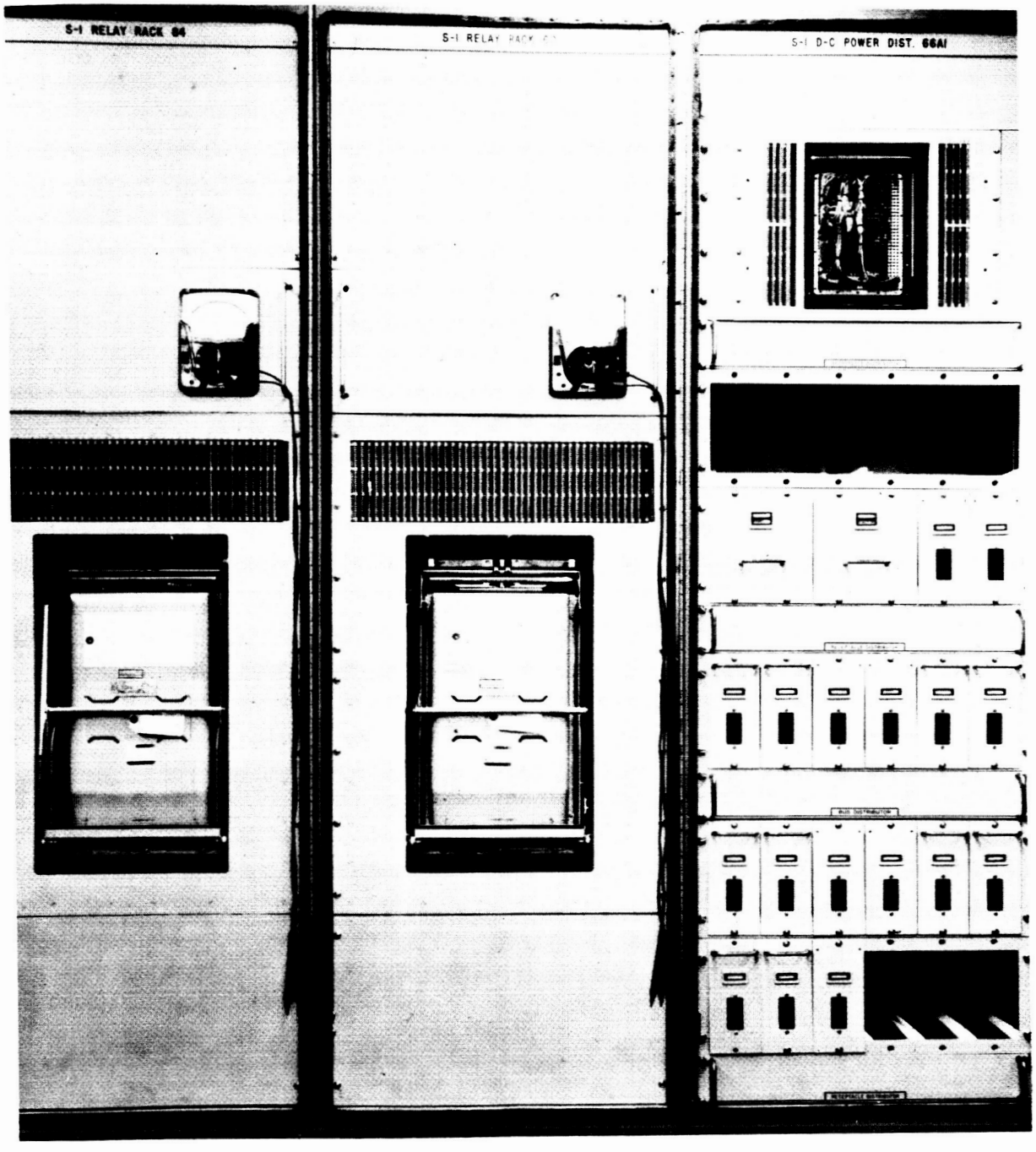


Figure 1. Power and Control Distributor Assemblies

You will be given a functional look at the Saturn V ESE checkout system and various ESE subsystems will be explained, but first let us take a look at some of the hardware involved. Typically, this hardware will be the standard modules, racks, panels, etc. used for the stage ESE and integration stations.

The modules are of two types: One is the 8-crystal can type relay module (Fig. 2) in which all connections are brought out to the connector and then to the patch panel; the second is the diode module housing 30 diodes with all connections (Fig. 3) brought out to an identical connector.

The equipment racks are standardized as follows: (1) 19-inch upright RFI shielded, (2) 24-inch upright RFI shielded, (3) 24-inch RFI shielded sloping, and (4) 19-inch RFI shielded sloping.

The panels and chassis (Fig. 4) are of a standard design and come in various heights. The desired components can be mounted in the various configurations required to provide the required functions.

The patch panels are a standard commercial design and are readily available on the commercial market.

The next step in the evolution is replacing the manual control of the checkout functions by automatic control utilizing a general purpose digital computer. This phase is being accomplished and is progressing in a manner to permit maximum assurance of a successful launch throughout the Saturn I Block II series. Upon completion, this phase will provide the necessary programs and hardware to permit full computer control by the time the Saturn IB program phases in.

SATURN V CHECKOUT PLAN

This completes the historical portion of this article and brings us up to date on present checkout philosophy and techniques. The Saturn V concept illustrates the overall systems checkout of a typical launch vehicle.

Physical Locations

Figure 5 presents an artist's conception of the Saturn V launch complex showing the Vertical Assembly Building, Launch

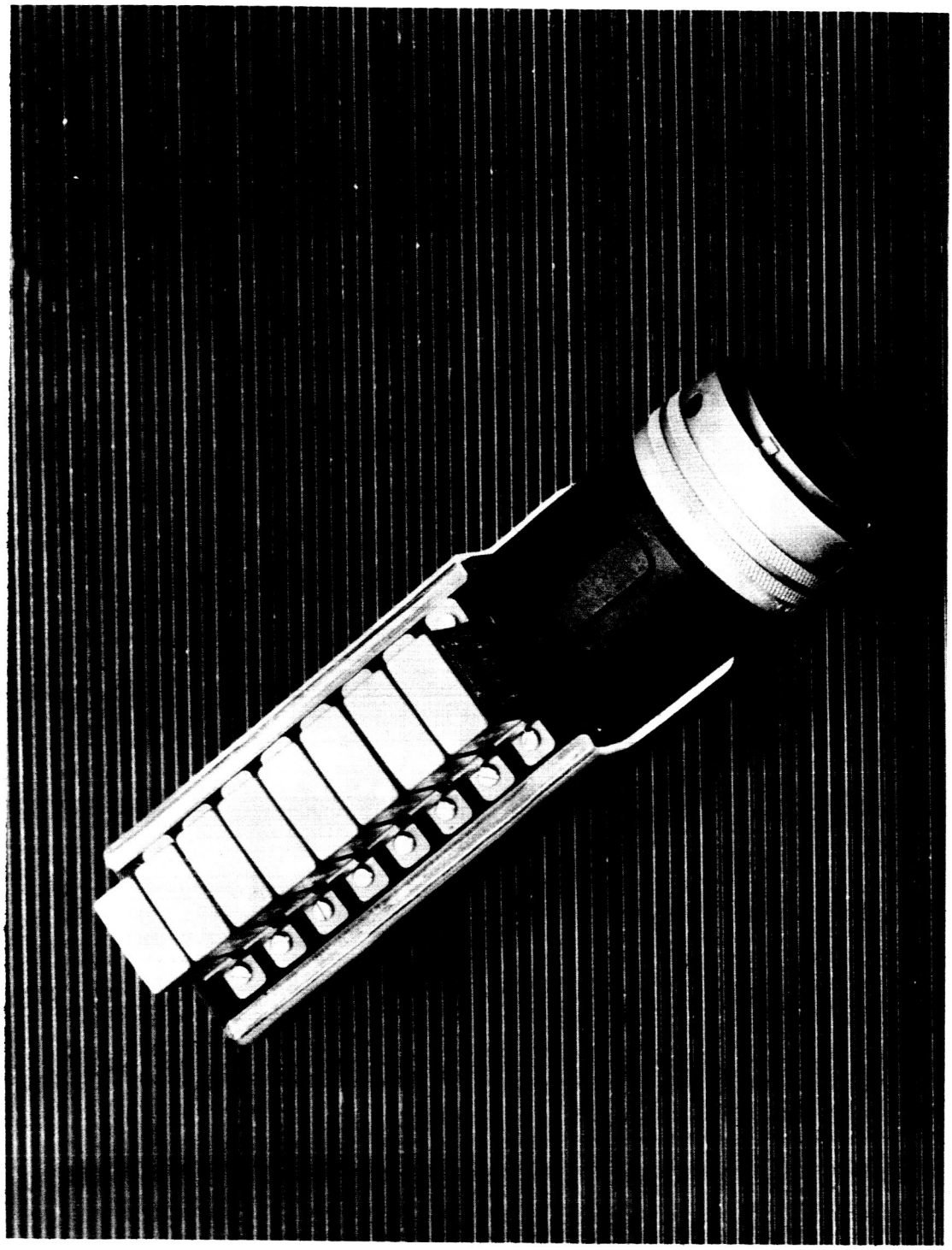


Figure 2. Relay Module Assembly

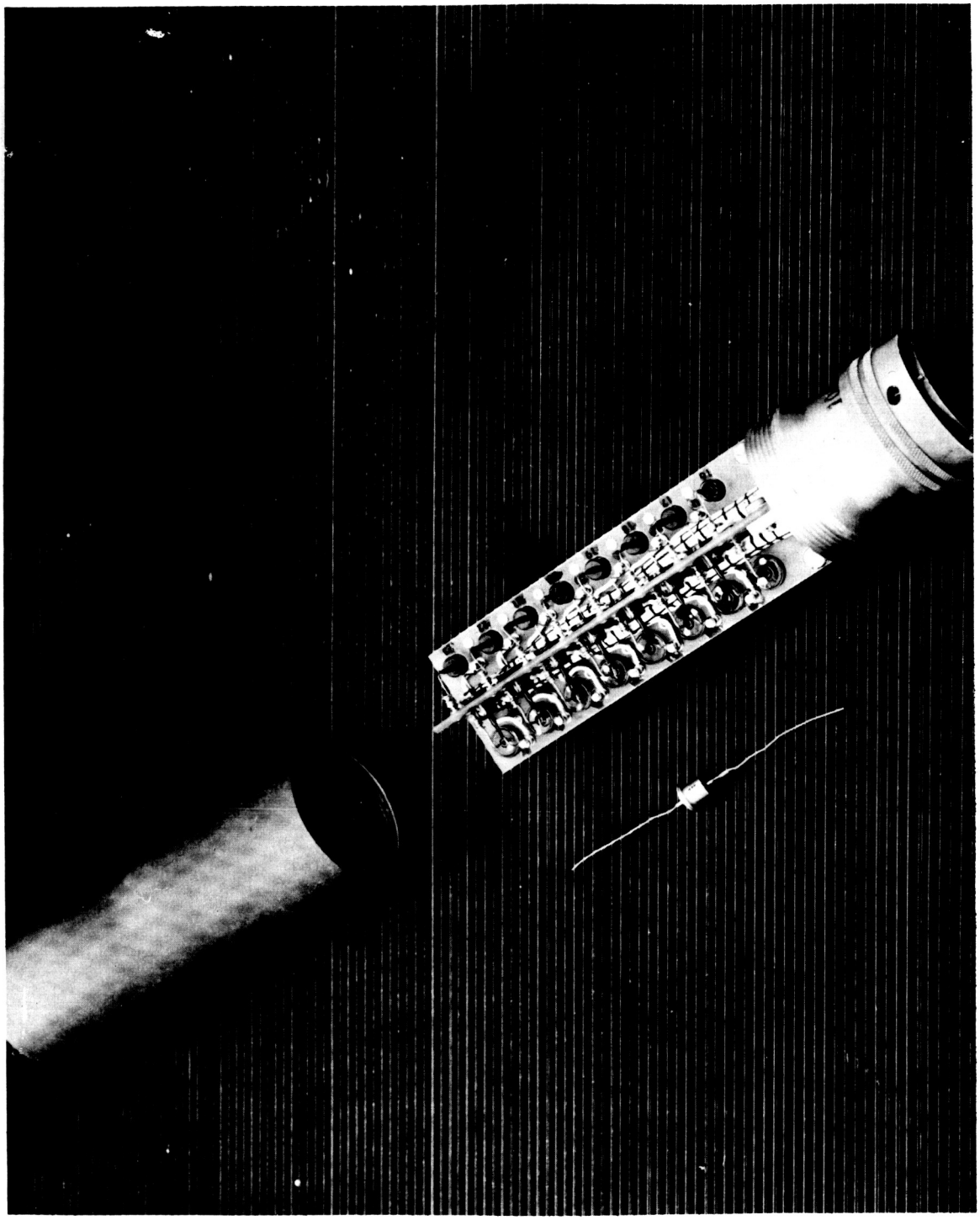


Figure 3. Diode Module Components

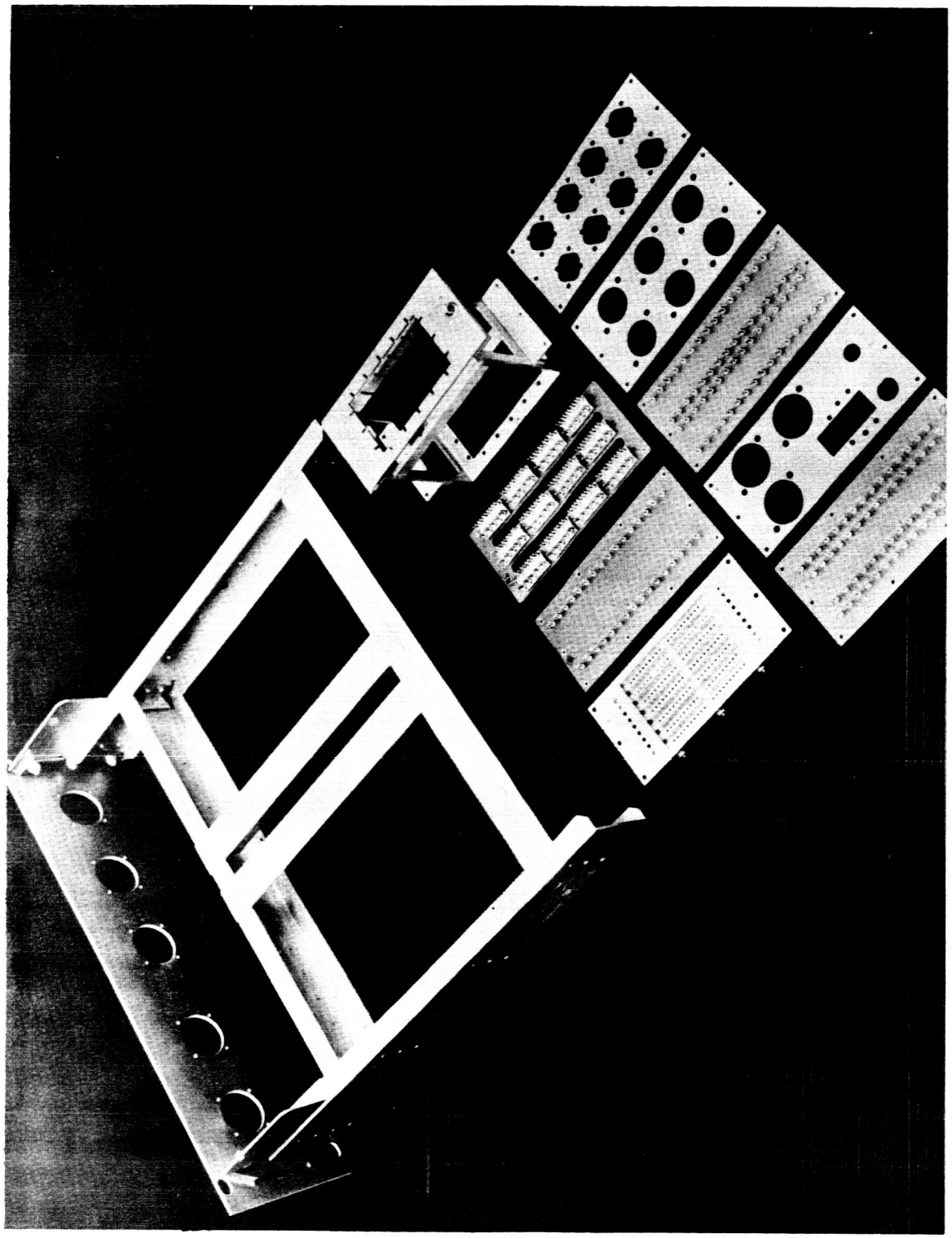


Figure 4. Standard Panel and Chassis Assembly

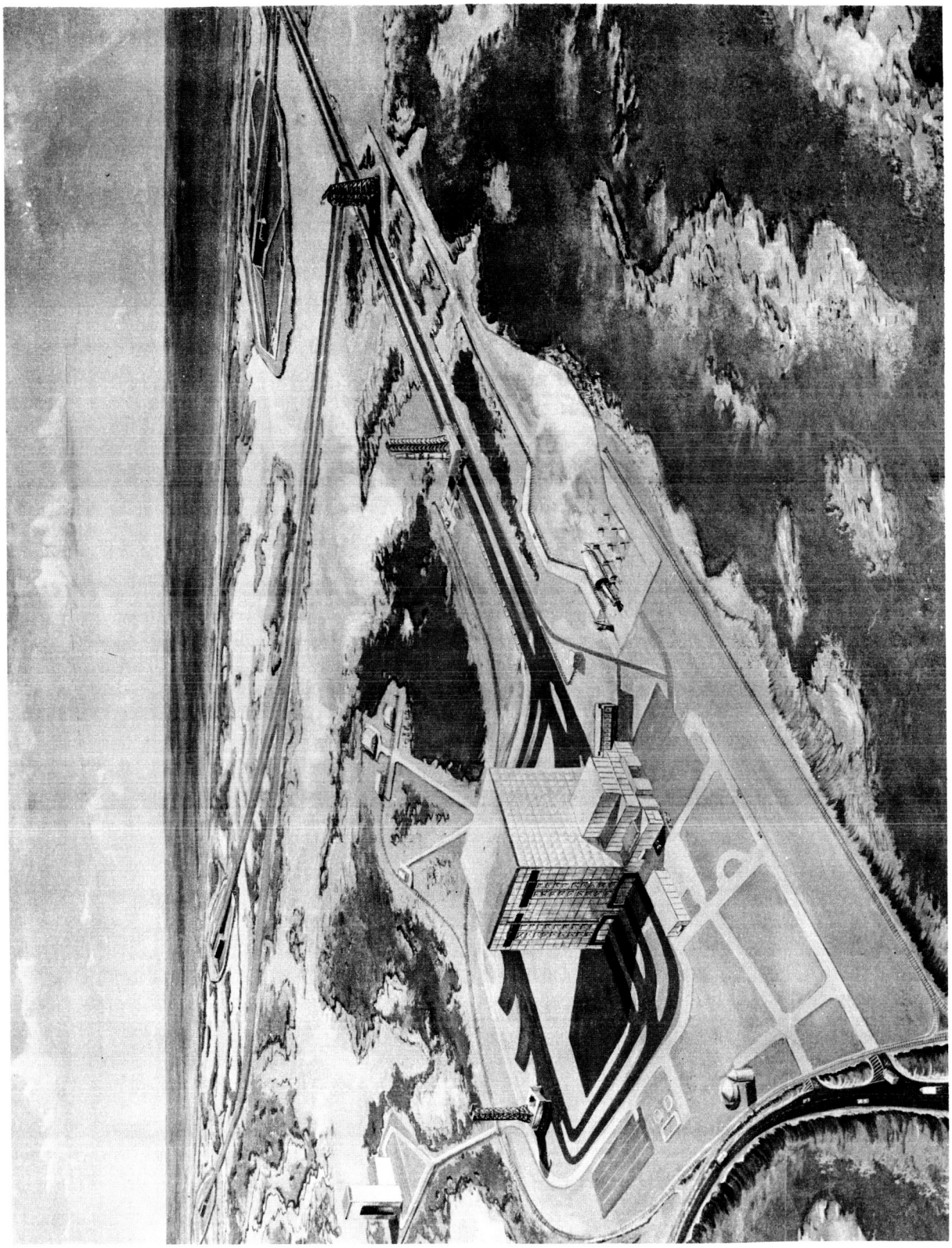


Figure 5. Saturn V Launch Complex

Control Center, crawler ways, and a Launcher Umbilical Tower in transit to the launch pad area.

The relationship of the Saturn V launch site area to the other Cape Canaveral operations is shown in Figure 6.

Figure 7 depicts some of the operations carried out in the Vertical Assembly Building, where the total vehicle is assembled and initial checkout operations are performed.

Following this, the checkout operations continue at the pad, culminating in the final countdown and launch as shown in Figures 8 and 9.

Figure 10 shows the first Saturn I heavy space vehicle (SA-I) launch from Cape Canaveral.

Equipment Types and Functional Relations

We will first explain the complete system, its individual component subsystems, and then describe the hardware to be used. The conclusion will be an attempt to predict future trends in checkout philosophy and equipment.

Figure 11 is a functional interconnect diagram for Launch Complex 39 at the Cape. It depicts the interfaces between the mechanical, pneumatic, and optical systems and the electrical systems.

Geographically, the ESE is divided into the area at the launch pad which includes the launcher umbilical tower (LUT), and the area at the Launch Control Center (LCC).

The equipment is of the following types:

(1) Stage ESE interfaces directly with the launch vehicle stages and contains the necessary logic and switching to permit safe checkout, launch sequence, and ignition. The laying and alignment equipment for the Instrument Unit and the optical link is also included here.

(2) The systems integration and distribution provides a means for directing the controlling signals to the proper stage

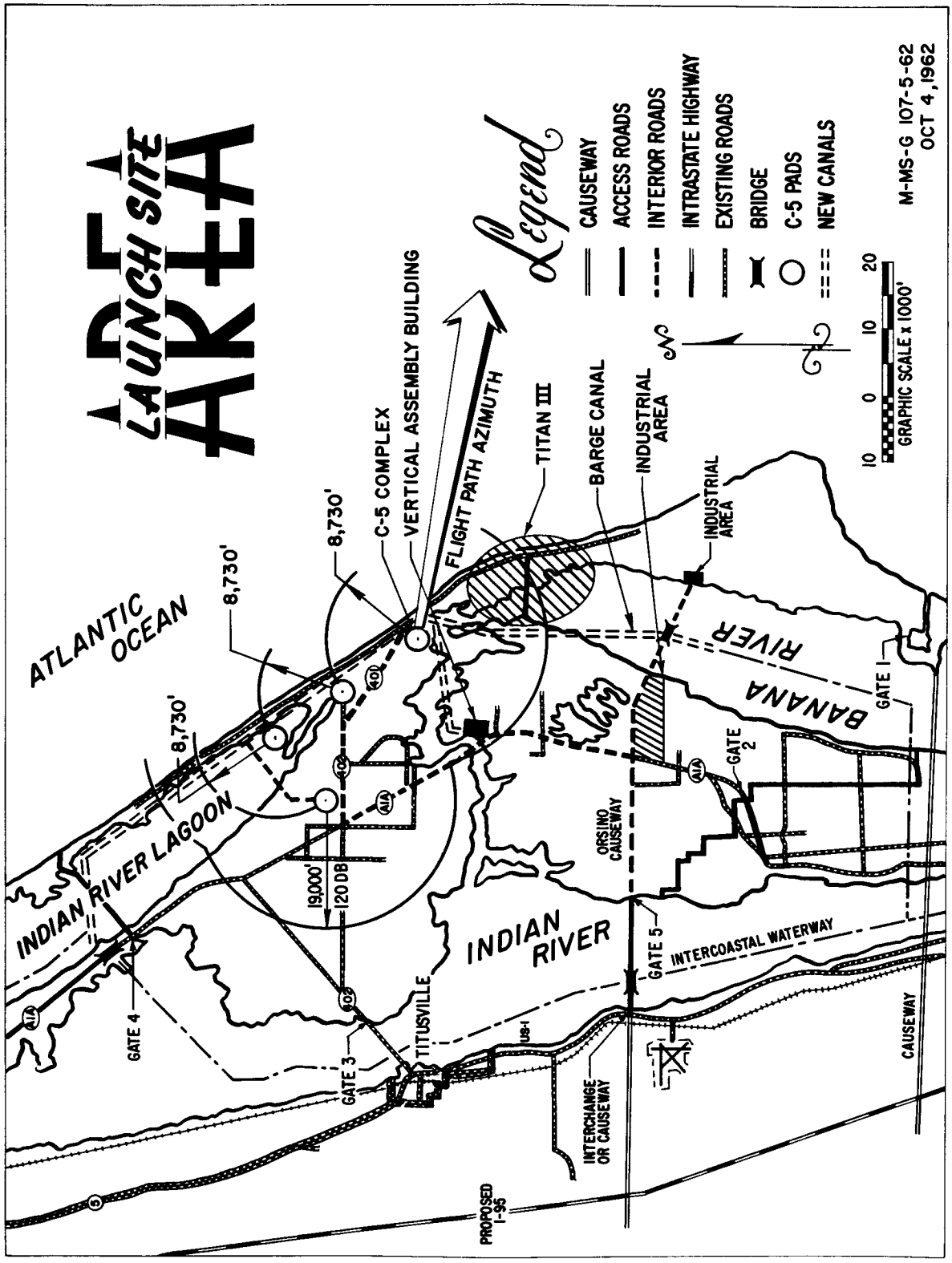


Figure 6. Cape Canaveral Area

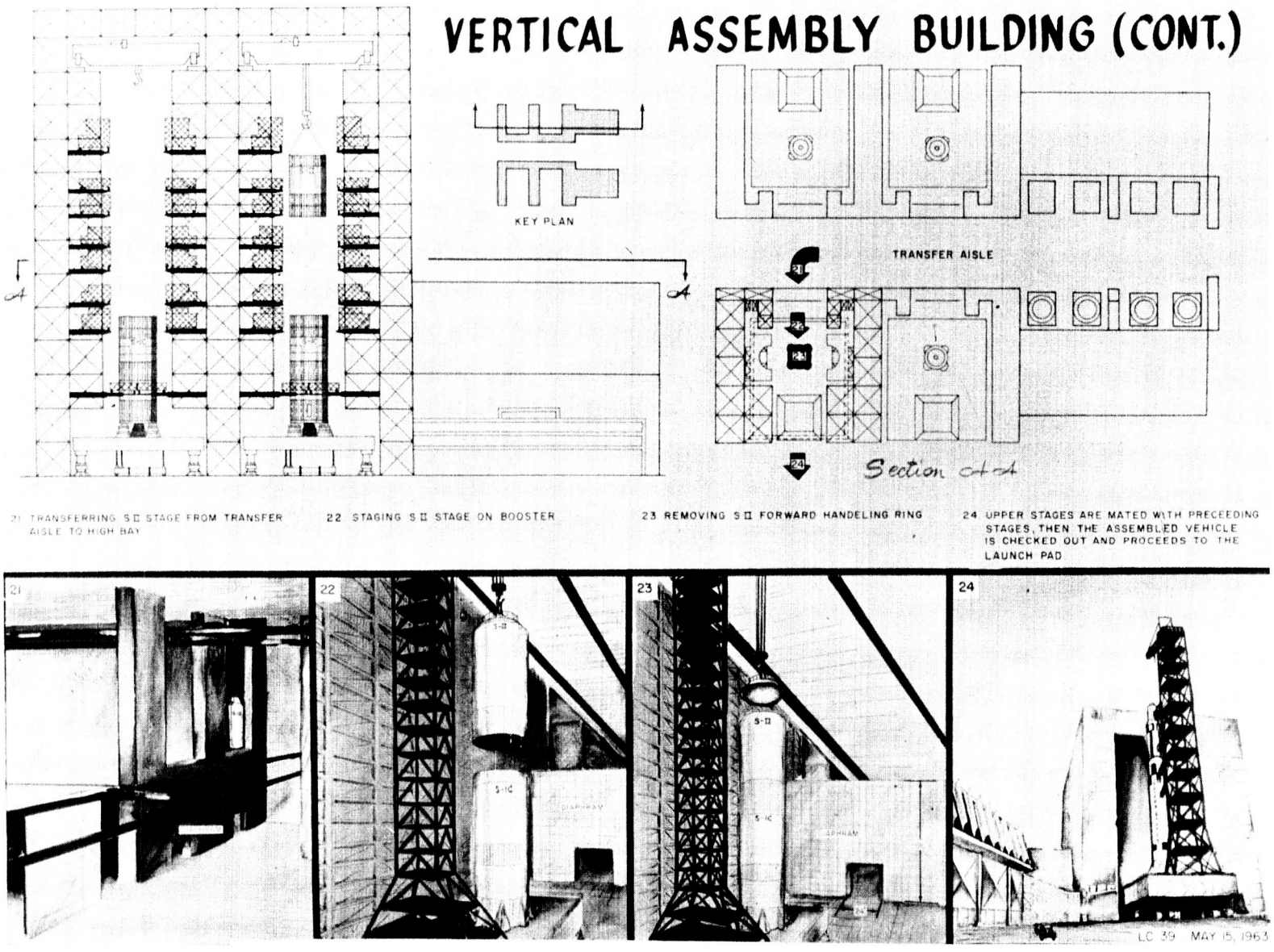


Figure 7. Vertical Assembly Building Operations

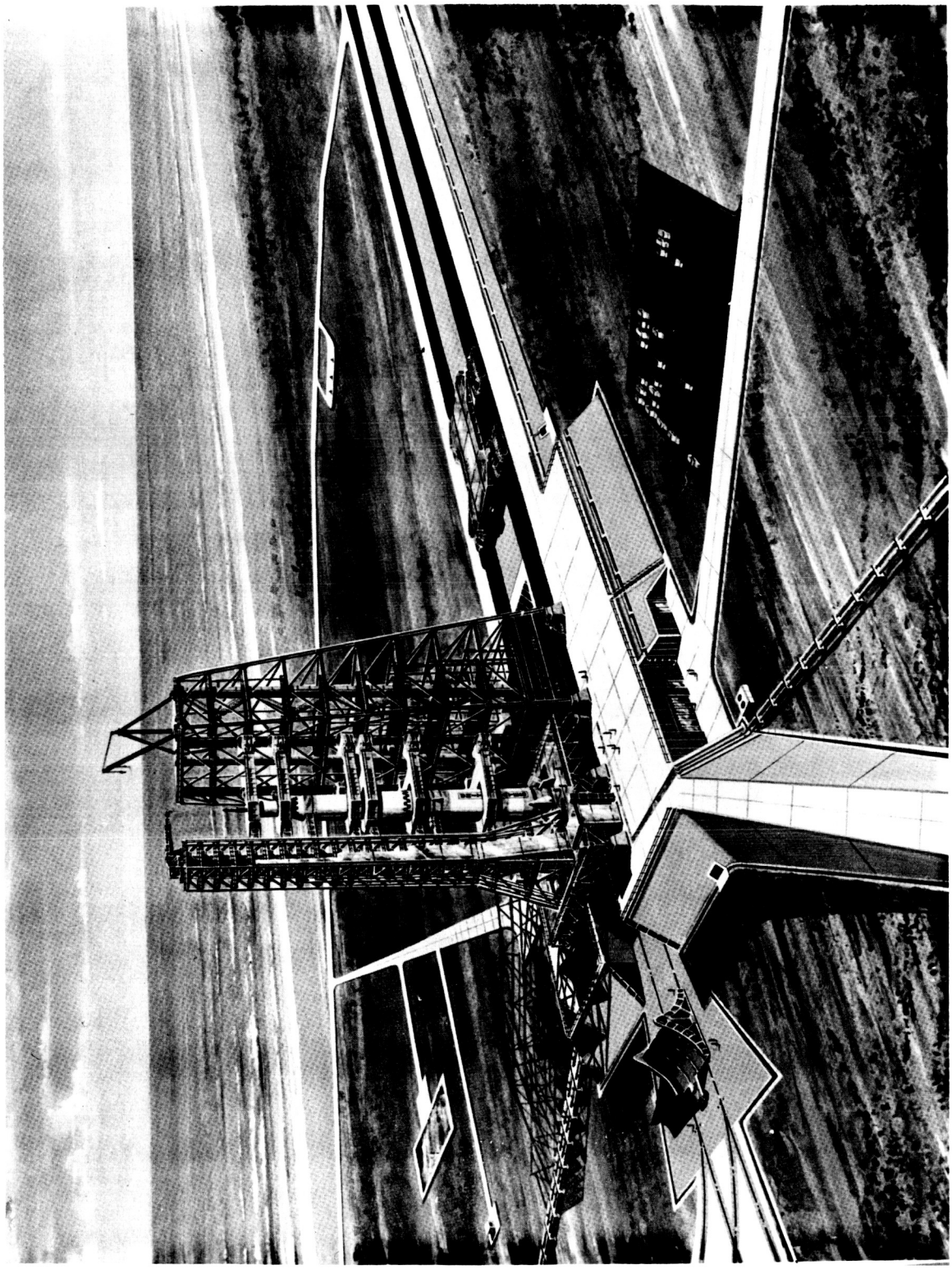


Figure 8. Launch Pad Area

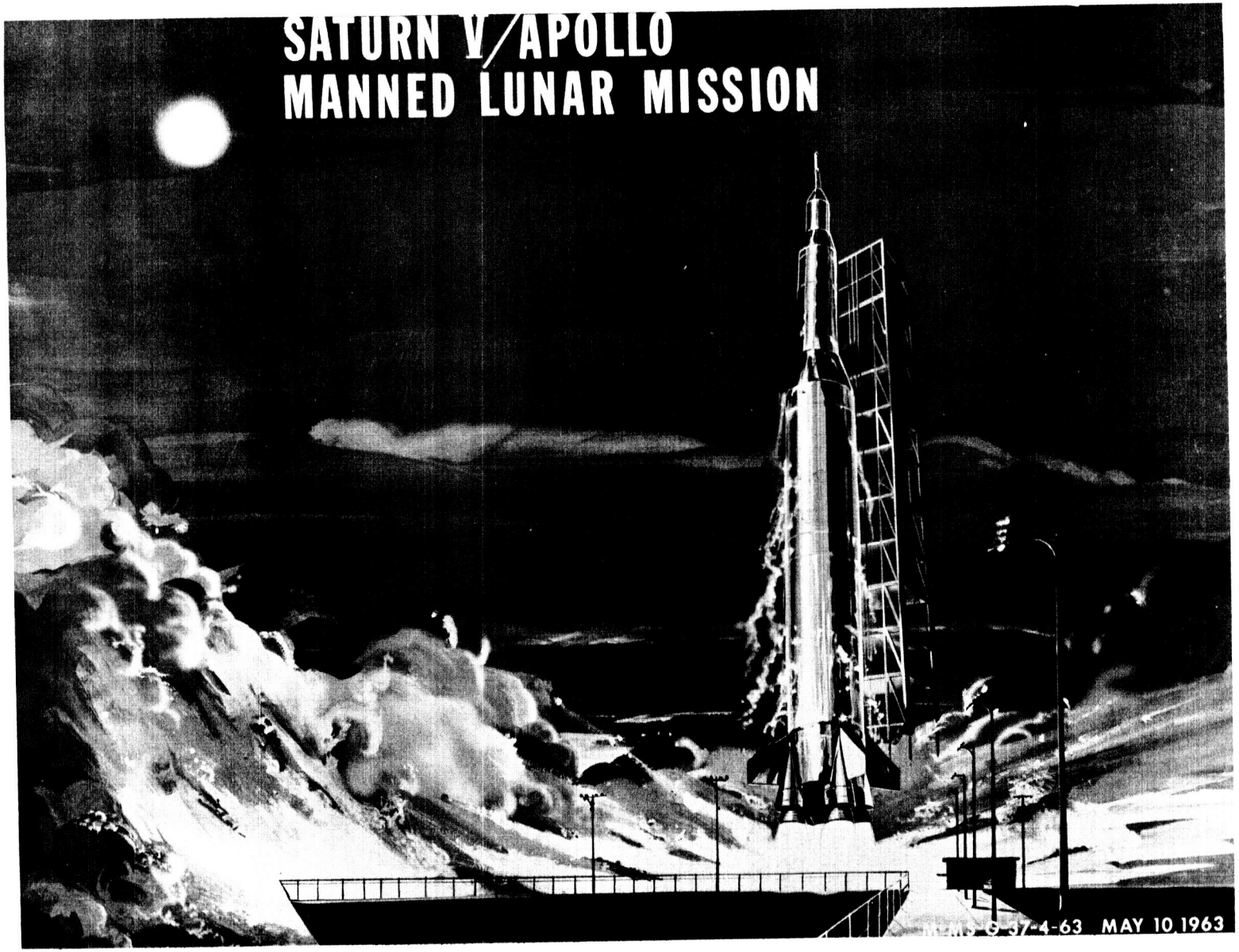


Figure 9. Saturn V Liftoff

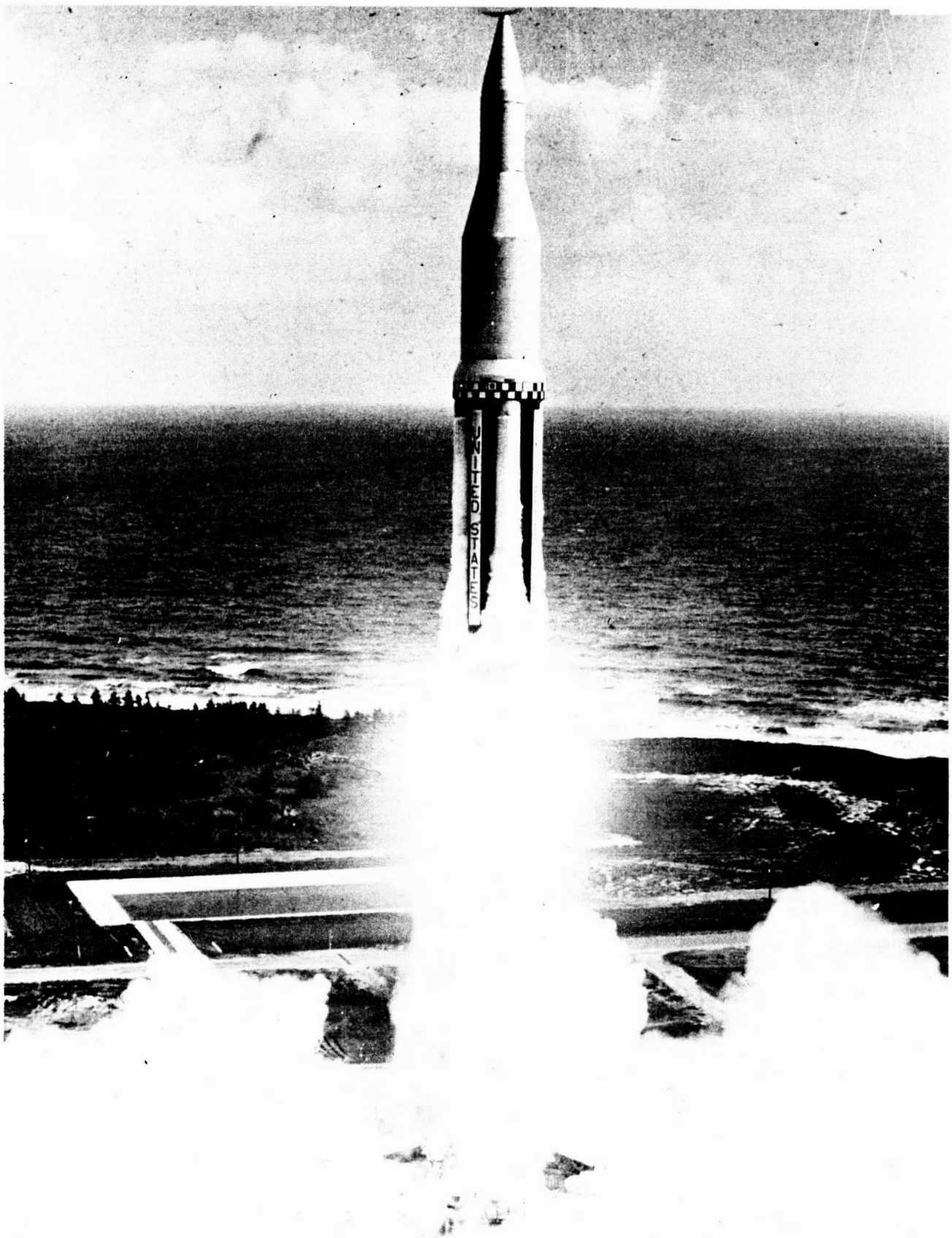


Figure 10. Saturn I Block I Liftoff

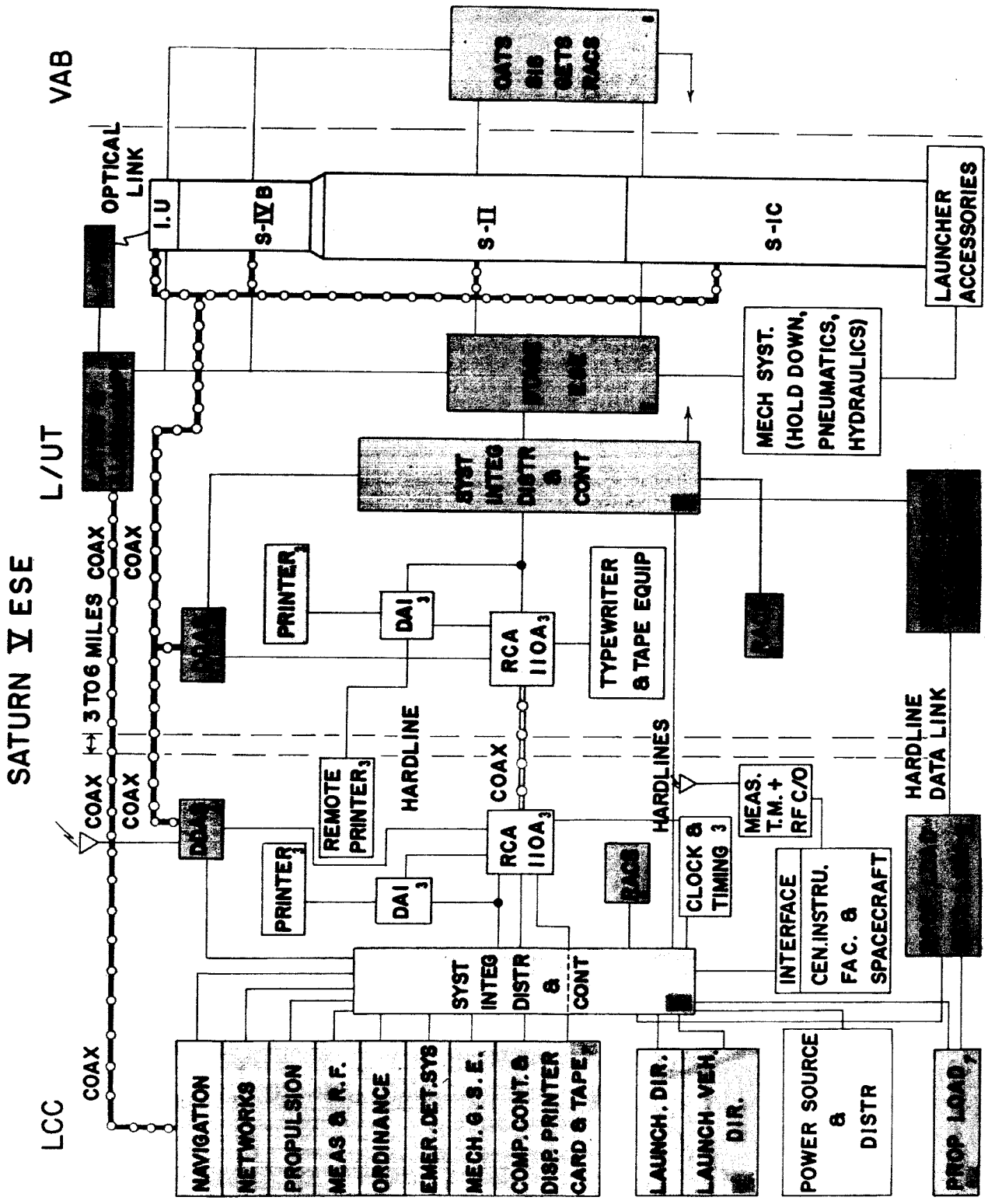


Figure 11. Functional Interconnect Diagram

ESE. This is the interface equipment between the computer and the stage ESE.

(3) The computer complex consists of the computer, data link, power system, flexowriter and tape control, input/output signal conditioning, clock and timing systems, discrete activity indicator, and the magnetic tape recorders. The LUT computer is used for running the programs for tests on the subsystems selected by the LCC computer which supplies the executive routines.

(4) The digital data acquisition system (DDAS) is a PCM/FM ground station for supplying stage information to the computer and display stations.

(5) Propellant loading and facilities equipment is mainly of a mechanical, pneumatic, and hydraulic nature for safe handling of LOX, RPI, and LH_2. However, the instrumentation and controls are largely electrical.

(6) Systems test equipment called GETS for ground equipment test set, SIS for stage interface substitute, and OATS for overall test set. Also, a remote automatic calibration set (RACS) is provided.

(7) Peculiar to the LCC are the control and display stations for control of the checkout, launch sequence, and ignition processes. These stations will be provided with the necessary meters and lights to indicate the status of the system they control. A CRT display will be available as a man-machine interface between the digital computer and operator. Also, a means is provided for interrupting a program by inserting a punched card; changes to the program can then be at the operator's discretion. Overriding emergency safing switches are provided on appropriate operational consoles which bypass the digital computer system and via hardwire permit controlling critical vehicle systems.

CHECKOUT FUNCTIONS

An examination of the role of electrical systems in the automatic checkout of a launch vehicle can best be accomplished by discussing the various functions that are required. The following topics are considered representative of these functions, but they should not be construed as being in the order of their importance:

(1) Power supplies and distribution
(2) Data transmission and distribution
(3) Operator displays and controls
(4) ESE self-check system
(5) Safety logic and interlocks
(6) Data conditioning - to reduce routine computer operations
(7) Reliable sequence operation through simplicity and redundancy
(8) Safing controls
(9) Individual recording of critical functions

Power Supply and Distribution

Ground power is required for checkout of a vehicle to conserve onboard battery capacity and to provide checkout and operational functions which cannot be provided by the vehicle power supplies.

The following types of ground power are required:

28 V dc
56 V dc
10 V dc
208 V and 115 V 400 Hz, 3 phase and 1 phase
208 V 60 Hz, 3 phase
115 V 60 Hz, 1 phase

In the Saturn complex, power generation and distribution is treated as a separate system. Power supplies feed into central power distributors. From these distributors, power is supplied to the various checkout racks of equipment and the main vehicle busses.

Typical power supply requirements for a Saturn vehicle are as follows:

Saturn 1st Stage:	two 250 A, 28 V dc
	one 60 kW, 208 V 60 Hz MG set
Saturn 2nd Stage:	three 250 A, 28 V dc
	one 200 A, 56 V dc
	one 60 kW, 208 V 400 Hz MG set

Saturn 3rd Stage: two 100 A, 28 V dc
one 250 A, 28 V dc
one 56 V, 200 A
one 40 kW, 208 V, 400 Hz

Instrument Unit: three 100 A, 28 V dc

Payload: two 100 A, 28 V dc

Besides the vehicle power supplies, auxiliary power requirements include:

Two 500 A 28 V dc supplies for propellant loading
One 250 A 28 V dc supply for clock and timing
One 60 kW 208 V 400 Hz MG set for platform motors and other 400 Hz loads
One 60 Hz 208 V power source for heater circuits

These are representative figures and are not intended to be interpreted as all inclusive.

Each power supply is remotely controlled by means of a power panel or through a digital computer. The functions of a power supply to be controlled are start-stop, voltage control, and output power on and off. Voltage, current, and frequency are monitored by means of meters and recorders.

All direct current power supplies are solid state devices consisting of input contactors, transformers, rectifiers, regulating circuits, filtering devices, protective devices, sensing circuits, and output contactors.

The quality of power required may vary with the purpose. Specifications for most of the 28 V dc supplies run as follows:

Static line regulation $\pm$.25%
Dynamic regulation $\pm$3 volts
Response time - 100 milliseconds for 98% recovery
Ripple - 100 millivolts, peak to peak

The direct current power supplies are equipped with remote sensing capability, which allows a set voltage to be maintained at a remote bus.

The large 208 V, 400 Hz power is obtained from conventional

synchronous motor generator sets. Smaller units are solid state devices.

Many of the vehicle loads are critical and damage will result from an interruption of power. Also, certain equipment must be operated during a power supply failure prior to shutting down for repairs. All of these requirements are met by placing batteries across all critical circuits. These batteries maintain voltage long enough to shut down the system.

Power distribution consists of air circuit breakers, fuses, contactors, shunts for dc current measurements, current transformers for ac current measurements, and voltage sensing devices.

Power is fed from the distributors to the using equipment by means of cables. Connectors are used to connect the cables to the distributors and the supplied equipment. On long runs of cable, wire as large as 5.062×10^{-4} square meters (1,000,000 circular mils) per leg will be used to cut down voltage drop. This is especially true on the 28 V systems.

Reliability is of major importance in the power supply and distribution system. Equipment must be used which has been thoroughly tested and proven. The system is also built with the idea of interchangeability. Modular construction is used on both power supply and power distributors. Ease of maintenance and quick replacement of parts are of prime importance.

Data Transmission and Distribution

The size and overall complexity of the Saturn V system place new and demanding requirements on data transmission and distribution systems. For the automatic GSE to function efficiently, it must have access to a vast amount of current and accurate vehicle data. In previous programs, telemetry data and data transmitted directly over hardwire lines have been used to meet this need. However, in the Saturn V program, the sheer quantity of data involved and the unprecedented physical separation of the Launch Control Center from the launch site make it necessary to provide a new and efficient data acquisition system. The design of the onboard instrumentation has been modified somewhat to provide the required data system. It is referred to as the digital data acquisition system (DDAS). In some special cases, data will still be transmitted directly over

hardwire circuits. Data will also be extracted from the various flight telemeter signals received via RF. The prime source, however, for prelaunch checkout will be the DDAS system.

The telemeter systems will be of the following types:

(1) PAM/FM/FM - Used for acquisition of low frequency analog data signals.

(2) PDM/FM/FM - Also used for acquisition of low frequency analog data signals.

(3) SS/FM - Used to transmit wideband data.

(4) PCM/FM - Used to telemeter slow changing analog signals requiring high degree of accuracy and certain discrete event occurrences. This system is used to make up the DDAS system.

(5) DDAS - A special modification is made in the airborne telemeters such that all of the PAM multiplexers within a stage are properly synchronized. Hardware is provided to sequentially sample these various multiplexers. This (PAM) signal is then digitized, formatted, and used to frequency modulate a 600 kHz subcarrier oscillator. This data signal is routed over wideband cable to the ground checkout system and provides highly accurate real-time vehicle checkout data. Each stage airborne DDAS system is associated with a ground station which performs the following operations on the telemetered information:

(a) Recovers the pulse train from the 600 kHz carrier

(b) Acquires bit synchronization

(c) Reconstitutes the PCM/DDAS pulse train

(d) Provides channel demultiplexing

(e) Accomplishes serial-to-parallel conversion

(f) Routes digital data to the checkout computer

(g) Generates analog signals for meter displays on the GSE panels

The DDAS is the prime source of data used by the computer for prelaunch checkout. Data are routed from each DDAS ground station into a computer interface system which is a core memory system. Data in the computer interface system are continuously updated as new data are received from the vehicle. The computer may select from this memory any data channel and will have instantaneous access to the currently available vehicle data.

A digitizing system is planned for the analog outputs of the telemetry ground stations. This data will be assembled in a DDAS type of format and placed in the computer interface with the DDAS data for comparison purposes.

It is planned to mount an airborne type of DDAS telemeter set on the LUT. Thus, the myriad of analog and discrete data signals that originate on the LUT can be transmitted to the LCC for remote monitoring.

Both the DDAS and hardwire techniques will be employed to transmit data between the LUT and LCC since both systems have relative advantages and disadvantages.

Operator Displays and Controls

The control and display console for each of the major systems is located in the LCC and provides the operator with both the status of the system under test and a means of controlling the test or altering the program as necessary.

The types of controls available to the operator are the conventional panel-mounted controls such as toggle switches, pushbutton switches, rotary select switches, thumb wheel code switches (binary or octal output), and switch lamps.

The displays used are lights to indicate vehicle status and discrete event happenings, meters of primarily a 20 microampere movement type for analog readout, elapsed time indicators, and digital counters and displays. There will also be a CRT display for status indication, checkout aid, and trouble shooting.

The indicator lights used are generally of a type that has a readily replaceable legend plate. This feature is invaluable in research and development programs where requirements are constantly changing.

The meters are usually of a small size to conserve panel space; but where accuracy requires, larger movements are used. Strip chart recorders are used to provide permanent records.

ESE Self-Check System

Prior to mating the electrical support equipment with the vehicle, a system self-check is performed to validate its functional correctness. These tests are performed on new equipment and follow any major equipment modifications. A test is always required between each launch because of rework resulting from the firing.

A ground equipment test set (GETS) is used to perform the self-check. This equipment is connected in place of the vehicle.

The self-check function falls in two basic categories; first, the requirement to verify all stimulating and measuring devices with their associated networks, and second, the requirement to exercise, as far as possible, those systems whose operations depend on elaborate data from the vehicle or whose operation cannot be pursued to their ultimate termination. The DDAS and hydraulic systems are in the latter categories.

Today the GETS equipment takes the form of manually-operated switches, potentiometers, meters, lights, etc., with a minimum of simulators, which exercise the "terminal countdown sequencer" and other sequencing equipment. It is the plan, however, to automate or computer control the GETS on the Saturn V system. This will allow special programs in the operational computer to perform these presently manual operations. By using the second computer in the Launch Control Center to simulate data from the vehicle, it will be possible to almost duplicate actual operating conditions, thereby increasing the validity of the self-check testing.

Safety Logic and Interlocks

The elements of safety for personnel and equipment are of extreme importance in either a manned or unmanned vehicle. The close proximity of highly combustible and corrosive propellants necessitates positive control of any critical valves, relays, etc. Positive control can best be maintained by positive

interlocks and hardlines providing positive type feedback indications. A system that exemplifies this situation is the fuel dispersion system commonly known as the vehicle destruct system (Fig. 12). The airborne portion of the destruct system is shown in this block diagram. The command destruct receiver (CDR) receives the engine cutoff and destruct command from the ground transmitter. Ground control to the firing unit consists of power "ON," command to internal power, and command to external power for the command destruct receivers. The same ground controls exist for the EBW firing units. The safe/arm block is a mechanical block that prevents the firing of the explosives regardless of any upstream equipment failure or command. Also, the CDR is interlocked on the vehicle by a relay which is de-energized by the vehicle lifting off the pad. All of these functions have positive indication feedbacks.

The operating conditions at the launch pad during countdown are extremely critical because the vehicle is fueled, pressure systems pressurized, and destruct explosives are aboard. Two requirements are of the utmost importance at this time.

The first is positive control and indications to assure that the destruct system is completely armed and available for operation at liftoff. However, it should be noted that a failure to arm should only result in a launch abort. The method used to assure that the vehicle is not launched is an inhibit relay in the "preparation complete chain." This chain is made up from a list of items which are considered critical requirements and will prevent the countdown from continuing past T-150 seconds. Since launch is prohibited by these interlocks, it is considered safe to use a data link/computer for issuing the arming command.

It is highly unlikely that more than one of the safety interlocks would fail and that a destruct signal would be inadvertently issued; however, if this condition should occur, the vehicle would be in an unsafe condition. To prevent this from occurring prior to the time the launch pad area is cleared, a manual interlock in the form of a key or manual switch is provided in series with that computer channel.

The second most important requirement during countdown is the ability to return to a safe condition if a hold is required or an abort occurs; this control and indication must be as positive as possible. Therefore, direct hardlines are

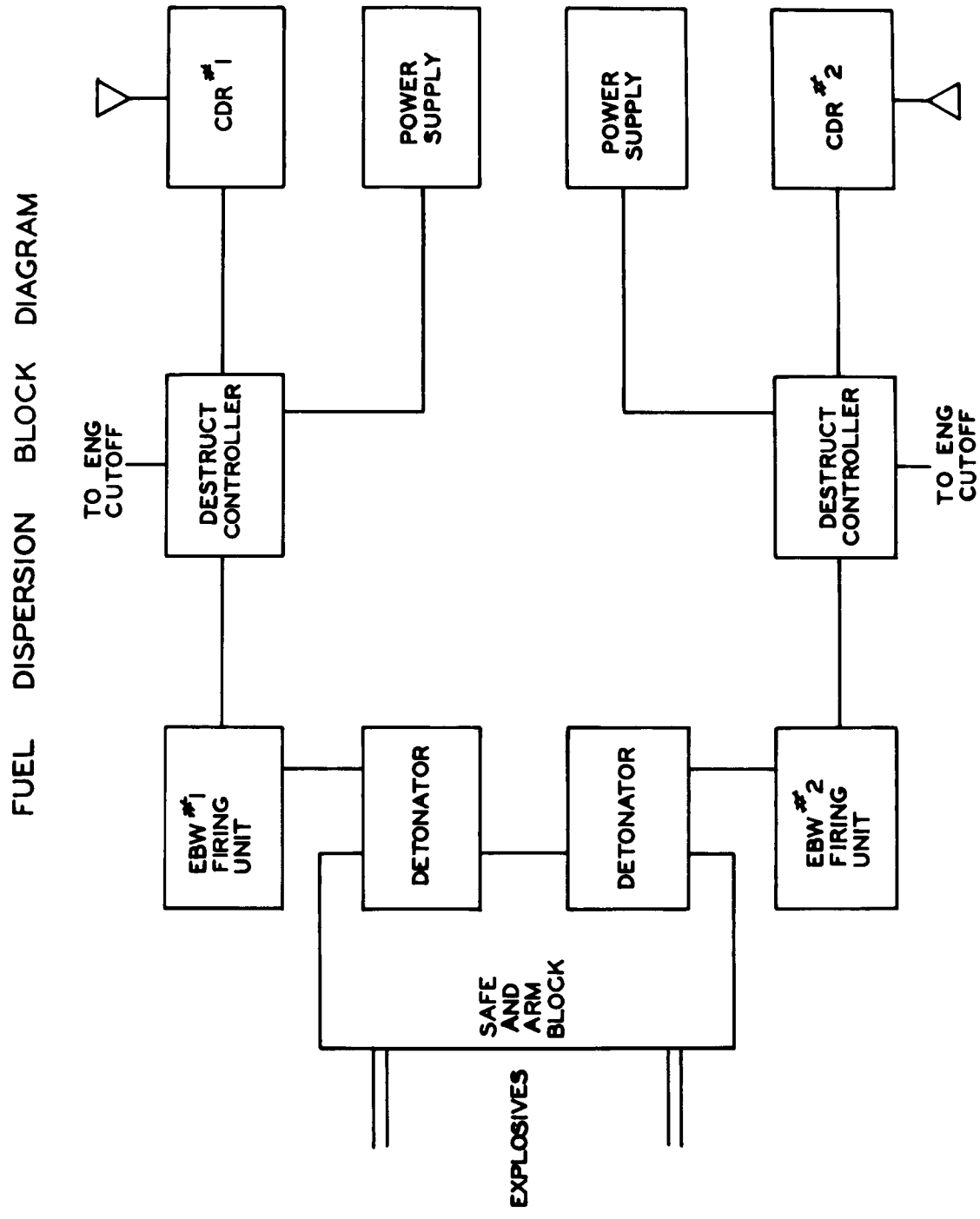


Figure 12. Fuel Dispersion Block Diagram

Figure 12. Fuel Dispersion Block Diagram

used for both command and indications. These lines bypass all automatic controls and data links. The functional components used in this system are the minimum number possible and consist of the most reliable switches, wires, and relays available.

A final recourse is made available if any of these components fail. This is the hardline control capability for removing power from any specific power bus or all power busses of the vehicle.

An example of critical, but non-hazardous interlocking can be found in the warm-up of the inertial platform used for flight control. This is of the air bearing gyro type and it is necessary that only preheated air be used. In this application, it is possible to utilize the computer to supply the proper sequencing of events, i.e., turn on heater, turn on air, monitor air temperature, and then arrive at a logical decision to continue the checkout or shutdown, depending on the air temperature.

Another example of safety interlocking is evident in the hydraulic system for flight control. This system usually has two temperature requirements for safe operation and a requirement that actuator control voltage be previously applied. Therefore, the command circuit to turn on hydraulics is interlocked by relays which are driven by oil and motor temperature sensors and by an actuator control voltage sensor.

Another example of safety interlock is in the component test operation. Checking of pressure switches requires that sufficient GN_2 pressure be available to operate the supply valve which supplies pressure to the pressure switches. Since no hazards of component degradation will occur if the valve supply pressure is absent, this interlock is performed by the computer program.

As a summary, the safety interlock system philosophy can be put into two categories:

(1) Catastrophic items that are hardline interlocked with multiple relay interlocks.

(2) Component safety items and minor hazards to peraonnel are interlocked within the computer program.

Data Conditioning

A large quantity of data must be processed and handled by the computers at the launch complex. If the simplest approach to data processing is used, i.e., maximum use of the computers for conversion, the computers will be become a bottleneck. In an effort to minimize this problem and to thereby increase reliability, various forms of data conditioners are utilized in the ESE, covering both discrete and analog type data.

Monitoring of discrete data is accomplished by the discrete activity indicator (DAI) through the digital data acquisition system (DDAS) and via umbilical hardline.

The DAI monitors some 1500 signals and supplies inputs to the computer. The inputs indicate:

(1) Number of the discrete which has changed

(2) Time at which the change occurred

(3) Direction of change, "off" to "on," or vice-versa

This device provides monitoring of these points with approximately a one millisecond resolution and has the additional advantage of reducing the computer load. The DAI is equipped with a printer which supplies a permanent record.

Reliable Sequence Operation Through Simplicity and Redundancy

Simplicity is the one factor that overshadows all others in obtaining reliability. This means not only simplicity in the basic operations of a system, but also simplicity in the relationship between each part to every other part in the system. A familiar term which is the result of inter-relationship complexity is "sneak circuit." In any new design - and sometimes old designs - there are sneak circuits. They can only be reduced; they cannot be totally eliminated except through extended use of the system or through costly and time-consuming design reviews. The key to our success in the design of checkout systems can be largely attributed to the use of "simplicity" as our watchword.

Certain critical sequences, for increased reliability reasons, are operated by an individual sequencer. For example, ignition of the rocket engines, pressurization of the propellant tanks,

ejection of the umbilical cables, and release of the vehicle at liftoff. Sequences of this nature are controlled and monitored through the use of solid state, core, and relay logic located in the ESE. These systems are kept independent to the maximum extent possible so they may be constructed, tried, proven, and then sealed against the effects of changes to the rest of the systems.

Twenty time-based functions required during the final seconds of countdown are also supplied (from the ESE) for reasons of reliability. The time base is needed to predict the exact instant of liftoff since the duration of certain operations vary, such as pressurization.

Other than these few critical operations, which could cause catastrophic failures, the computer has complete control of the system.

Safing Controls

At any time during vehicle prelaunch preparations and prior to liftoff, an emergency condition may arise which requires the restoration of the vehicle to a safe condition. Safe condition is defined as safe for personnel to work with or around. The vehicle will be restored to a safe condition by relay logic operating independently of the computer.

Equipment that affects stage safing is not contained in explicit safing equipments per se, but is distributed throughout the electrical GSE, mostly in the networks rack, propulsion racks, and pneumatic consoles. All of this equipment is supplied electrically by a ground bus paralleled by a battery system to safe the vehicle in the event of a power supply failure.

If a "safe" vehicle condition is one in which personnel can work, then some propellants must be unloaded. In any event, the procedure for stage safing is semi-automatic. Certain emergency cutoff signals automatically initiate the stage safing sequence. Such signals include bus voltage failures, stage pneumatic control spheres over-pressure, engine rough combustion, thrust failure, fire detection alarms, and others. Observer cutoff may also be initiated.

When cutoff occurs, the engines shut down automatically through their cutoff sequences, the stage busses are automatically

transferred to external power, and external power is applied to selected stage control and monitor busses. Automatic vent down of the propellant tanks may be accomplished if necessary. High pressure bottles on board are vented manually. Safe/arm devices, such as those in the command destruct system, are motorized to the safe condition and the status read out on hardwire.

The safing operation is controlled via hardwire to provide the maximum in reliability. This hardwire will be controlled from the control and display consoles and go directly to the vehicle with a minimum number of connections.

Individual Recording Of Critical Functions

On the present Saturn I system, approximately 100 discrete functions are monitored by event recorders and recorded on strip charts. Monitoring of the majority of these functions is also accomplished by the digital computer. In the near future, the addition of a discrete activity indicator to work with the computer will be made. The DAI will scan the discrete functions and flag the computer only when a change in the state of any function occurs. This will provide a smaller increment of time between successive scans of the functions without tying up a major portion of the computers capability. The computer can then display this information as required. It is anticipated that this system will eventually replace the strip chart recording.

Discrete recording serves two main purposes: One, it is an invaluable aid in verifying the proper functioning of the equipment during checkout. Two, it provides a history of the sequence of events for circuit analysis. In most cases of component malfunctions, it would be impossible to isolate the trouble and determine the cause without this information.

To fulfill the requirements for the above two uses, the functions must be listed as critical and include such items as valve operations, bus voltages (within predetermined limits), pressure switch operations, feedback from electrical components, mechanical operations, limit switches, etc.

Analog recording is presently accomplished on strip chart recordings of various makes. Such functions as bus voltages and currents, pressures, temperatures, flow rates, position indications, etc., are visually monitored during checkout and launch.

Predetermined limits are also presented on these charts. For many functions, such as temperatures and pressures, the rate of change may indicate trouble before the redline limits are reached.

To accomplish these recordings by strip charts requires hardwire interconnections or telemetry links with the inherent problems of noise and stray pickup. It is planned to convert most of the analog signals to digital form by use of the digital data acquisition system and transmit them to the computer over coax or RF link. The computer can then be programmed to display the functions in the manner as required.

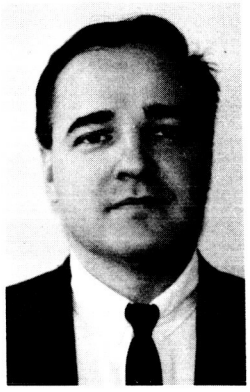
FUTURE TRENDS

In the future, more reliance will be on computers for decisions. This can only be accomplished through a greater supporting role by the electrical systems. The reliability and speed of transmission systems must be increased. The size and speed of analog and digital monitoring systems must be increased to provide the data necessary to make these decisions. A more extensive knowledge of the system must be gathered to implement the programs for fault isolation and fault prediction through trend analysis.

The effect of automation is making a deep impression on the checkout and operation of space vehicles. At Cape Canaveral, we have computers in control of certain checkout functions on the Saturn I vehicles. They are not only completely changing the man-machine relationships, but also finding trouble and problems to levels of detail and complexity previously unknown in the world of checkout equipment. This new capability of speed and sensitivity is not without its problems; however, considerable efforts are being expended in the area of radio frequency interference suppression. There have also been many problems with previously unimportant characteristics, such as relay contact bounce and inductive ringing caused by large solenoids. We have experienced problems with intermittent signals saturating the digital type of serial operations to the exclusion of all other data. All these problems are eliminated as they are recognized, but the advent of computer-controlled automation has caused a considerable realignment and readjustment of the role of the electrical systems. The effects and impacts will be felt for a long time to come.

OPERATIONAL COMPUTER SYSTEM

Fred S. Wojtalik



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Mr. Wojtalik received his BEE degree (Michigan State University). His work requires that he accomplish advanced technical planning in the area of operational process control for the Saturn Operational Computer System and orbital checkout functions of the vehicle-borne computer complex. His experience in ground-support equipment has been gained through design and development projects for the Redstone, Jupiter, and Pershing missiles as well as the Saturn vehicle program. Present position: Technical Assistant to the Division Chief, Guidance and Control Division.

OPERATIONAL COMPUTER SYSTEM

by

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ABSTRACT

The successful development of automated ground support equipment and sophisticated digital technologies for the checkout and control of large space vehicles is being achieved through the application of digitally controlled equipment, which is designed to provide accuracy, reliability, and speed, and through machine programs written to enhance and preserve the analytical and decision making capabilities of the test operator.

The central data processor and interface equipment that comprise the Saturn operational computer system for launch site checkout and control are described. Program preparation and control and system utilization objectives are also discussed.

INTRODUCTION

For the past several years the Marshall Space Flight Center has been actively engaged in the development and application of automated hardware and techniques to the testing and control of large space vehicles. This program involves a large number of private concerns and encompasses almost every part of our country.

In illustration, the Saturn operational computer system will be or is being utilized as a part of the automated test equipment in the following locations:

1. Systems Development Facility, Marshall Space Flight Center, Huntsville, Ala.

2. Instrument Unit Checkout, Marshall Space Flight Center, Huntsville, Ala.

3. Booster Stage, Static Test Stand, Marshall Space Flight Center, Huntsville, Ala. and Mississippi Test Operations.

4. Booster Stage, Factory Checkout, Marshall Michoud Plant, New Orleans, La.

5. Launch Site Checkout and Control, Launch Operations Center, Cape Canaveral, Fla.

With the advent of large space boosters and vehicles of the Saturn I, IB, and V configurations, systems designers recognized early in the program that automation was needed because of the increasing complexities associated with large space vehicle checkout and control. This situation would, if not adequately handled, degrade the dexterity and analytical capabilities of our operating personnel when they are required to function under extremely tight schedules. Automation, when properly applied, could relieve the man from much of the burdensome functions of checkout and free him to focus his attentions on the challenging and more important analytical aspects of vehicle checkout and control. An additional benefit derived from successfully applied automation is the standardization of testing procedures and results which are prime requirements for valid data evaluation.

The Marshall Space Flight Center's Automation Plan is the result of experiences gained in many years of successful missile technology and the progressive evolution of checkout equipment and techniques. Relative to the areas previously mentioned, it establishes the utilization of a general purpose, process control, digital computer and the application of advanced digital techniques to develop an efficient man and machine vehicle checkout and control system.

The remainder of this presentation will be divided into the following topics:

I. Characteristics of the Saturn Operational Ground Computer System

II. Programing Plan

III. Operating Objectives

I. CHARACTERISTICS OF THE OPERATIONAL COMPUTER SYSTEM

This presentation describes the operational computer equipment which is being developed for Launch Complex No. 39, located at the National Aeronautics and Space Administration's Launch Operations Center, Cape Canaveral, Florida. This vehicle assembly, preparation, and launching complex will be used for the Saturn V vehicle program. With regard to launch operations, two facilities are of prime importance, the launcher-umbilical tower and the launch control center.

Launcher-Umbilical Tower - A mobile launching structure that allows vehicle assembly and phase one checkout to occur within an enclosed assembly area. The launcher operational computer is located on the second floor of this structure.

Launch Control Center - Operational nerve center for Complex No. 39 vehicle checkout. Located from three to seven miles from the launching pads, the operations personnel within the launch control center depend on local equipment to provide comprehensive current vehicle status information as well as vehicle and complex control. The control center operational computer is part of the electrical system equipment within this area. When received from the stage contractor, the S-IC booster stage will be placed on the mobile transport and launching structure. The checkout equipment within the launcher-umbilical tower and launch control center forms a complete system of ground support equipment which remains essentially alike from the first tests of the S-IC booster stage, through vehicle assembly, final launch preparation, and launch itself. The intent is to establish a pattern of checkout procedures and operation that remains unchanged except for actual physical distance between the operations personnel within the launch control centers and the vehicle positioned on the launcher. While in the assembly area, separation between computers is approximately 1500 electrical feet. This distance can increase up to seven miles when the vehicle is moved to its launching area. An important feature of this arrangement is that all electrical signal lines between the vehicle and its launching checkout equipment remain intact throughout the complete checkout operation.

The equipment, which is located in the launcher-umbilical tower beneath and alongside the vehicle, will receive and have access to all operationally significant vehicle and launch site facility electrical signal

lines. These signal lines, routed through stage umbilical and facility distribution centers, will be accessed and energized, as required, by the operational computer system within the launcher-umbilical tower. Normal operation will evolve around a set of assigned, predetermined test and control routines. Under program control or by operator demand from the launch control center, important vehicle test data and status information will be transmitted from the pad area via a digital data link to the operational computer within the launch control center. The operational computer system within the launch control center will be programed to communicate with the test operational system. Summarizing, it must accept new and out of sequence test requests, transfer these requests through the data link to the launcher-umbilical tower system, receive and disseminate new and stored information to operational display areas, and test and control locally available signal lines.

The tandem arrangement employed in the computer installations of Complex No. 39 provides the following additional benefits.

1. Task to be performed is independent of data transmission bandwidth.
2. Local launcher evaluation and control.
3. Self-check flexibility.
4. Modification of system input-output capability is possible without hardware modification.
5. Avoids dominance of prime control by secondary data.
6. Programable local priority assessment.
7. Redundant capability in storage, computation, and data gathering.

The Saturn operational computer system is composed of the following basic units:

1. Central Data Processor
2. Peripheral Input-Output
3. Display Equipment
4. Data Link

1. <u>CENTRAL DATA PROCESSOR</u>

a. <u>Requirements</u>

(1) Response

(a) Discrete

(b) Analog

(2) Selective scan

(3) Independent data channel operation

(4) Storage and retrieval for display support

(5) Computational capability (minor)

(6) Automatic priority interrupt

(7) Power failure capability

(8) Isolated grounds and designed to eliminate radio frequency interference

(9) Maximum computer system availability

(10) Ruggedized construction

b. Characteristics

(1) Type: RCA-110 - An internally stored program, process control, general-purpose digital computer designed specifically for real-time control in industrial applications

(2) Mode of Operation:

(a) Parallel transmission

(b) Serial arithmetic

(3) Logic: Single address

(4) Word Structure:

(a) Instruction: 9-bit instruction, 3-bit address modifier and 12-bit address field

(b) Data: 24 bits

(5) Index Registers:

(a) Six 15-bit index registers

(b) One 15-bit indirect address index register

(6) Memory:

(a) Magnetic core storage (available in 4096 word modules to a total memory of 32,768 words). Access to all 32,768 words of memory is accomplished through the utilization of an index register for purposes of address modification.

(b) Magnetic drum storage (32,768 words)

(7) Timing:

(a) Memory access time is 10.25 μs.

(b) Word time is 28.85 μs.

(c) Clock rate: 936 kHz

(d) Add time: 57.7 μs

(8) Circuits: Solid state

(9) Arithmetic: Binary

(10) Input-Output:

(a) Eight, individually addressable, 24-bit input-output registers (IOR)

(b) Eight, individually addressable, 24-bit input-output sense lines (IOS)

(c) Eight, individually addressable, 24-bit input-output address lines (IOA)

(System utilization of these registers can be seen from the attached assignment charts)

(d) Six bidirectional input-output data channels (IODC) that operate on a time-shared basis with the central data processor. This feature provides a capability for accomplishing input-output operations without interrupting the operationally significant main computer program. Assignment of an IODC to any portion of high speed memory is under program control. Once assignment is made, information transfer and synchronizing control are accomplished by the IODC circuitry. The IODC is a vital feature of the Saturn operational ground computer system. It allows inputs from the discrete event indicator, digital data acquisition system

and data link to enter computer memory with a minimum of supervision time from the central data processor. IODC allocation is as follows:

IODC No. 1 - Line printer or typewriter, magnetic tape units, magnetic drum, paper tape punch and reader, and card punch and reader

IODC No. 2 - Display Systems

IODC No. 3 - Data link

IODC No. 4 - Discrete signal activity indicator

IODC No. 5 - Digital data acquisition system (DDAS)

IODC No. 6 - Magnetic tape units (All tape units operate in low density IBM format. This feature is required for standardization purposes.)

(e) Interrupt System:

1 Internal program interrupt

2 Four-level external automatic priority interrupt

3 Input-output automatic priority interrupt

2. PERIPHERAL INPUT-OUTPUT

a. Discrete Signal Input: 1512 bilevel (0 or +28 VDC) inputs.

b. Discrete Signal Output: 1008 bilevel (0 or +28 VDC) outputs.

c. Analog Input: 300 signal inputs comprised of 0 to ±100 VDC, 0 to 150 V (400 Hz) and 0 to 150 V (60 Hz).

d. Analog Output: 72 outputs are provided through two channels of D/A with suitable amplification to provide a capability for 0 to ±100 VDC and 0 to 30V (400 Hz).

e. Paper tape punch and reader.

f. Card punch and reader.

g. Magnetic tape: 2 master tape controller units and 4 transport units. Expandable to 20 transport units.

h. Display Power and Control Logic: Capable of controlling 18 direct-view storage tube display units.

i. Special Input-Output:

(1) Airborne Guidance Computer: This input-output capability is provided through one of the central data processor IOA groups. Voltage level conditioning and synchronizing control circuits are required to enable direct communication with the airborne system.

(2) Clock Inputs: Access to the Eastern Standard Time and the countdown clock is provided through this input. These inputs are implemented on IOS lines.

(3) Spacecraft: A 24-bit input-output register is utilized for communication with the Saturn spacecraft checkout system. Programing that accomplishes synchronizing between both checkout systems during launch countdown activity is being developed.

(4) Digital Data Acquisition System: An IODC is assigned for this important input. The DDAS system makes use of the onboard stage PCM (pulse coded modulation) telemetry system and provides the computer system with an accurate digitized input of onboard analog and digital signals. All vehicle stages of the Saturn vehicle will utilize PCM and DDAS systems to a maximum. Individual signals as well as signal repeat modes are provided to the computer system through a core random access interface. An additional feature of the DDAS is the capability to receive inflight PCM telemetry data and to provide this as an input to the Saturn operational ground computer system for quick-look evaluations after lift-off.

3. DISPLAY EQUIPMENT

Operator displays, which are utilized in the Saturn vehicle program, can be divided into two groups:

a. Those which receive their data primarily from sources other than the computer. Lights, meters, and recorders are examples of displays in this category.

b. Those which receive their data only from the computer. The operator control and display console is in this category.

The Saturn operational computer utilizes an internally-stored program and, therefore, has the inherent ability to accumulate large volumes of data in a very short period of time. Evaluation of this data is contingent on the methods utilized to display and communicate this data to the test operator. Means must be provided to facilitate rapid evaluation of test data, to determine correlations, and to support trend analysis, malfunctions, and the timing of event. To achieve the degree of control and monitoring capability that is required by our test operators, it was decided that a display system composed of many individual consoles, as opposed to a central display, was necessary. With this type of display and associate control panel, experimentation to determine the extent of automation, methods to improve man and machine relationships, and the development of techniques for remote station control of the operational computer could be provided at minimal expense.

The display equipment provided as part of the operational computer system has the following characteristics.

(1) This display consists of one rack containing the input-output circuitry and power supplies for the display device and a console that contains all controls and the display device itself.

(2) The display device is a 21-inch shaped beam, direct view storage tube. Viewing time of this tube without rewriting is 5 minutes minimum without objectionable deterioration of display quality. The tube can display any combination of 62 characters which includes all the standard alphanumeric characters as well as additional special characters.

(3) The communication links between the RCA-110 computer system and the display device utilize a six or seven-bit code for information transmittal. This depends on the requirement for tabular or graphic presentation.

(4) The speed at which information is accepted for display is 10,000 characters per second. In the "tabular" mode, a format of 50 characters by 32 lines is possible. In the "graphic" mode, an array of 168 "X" increments and 217 "Y" increments is possible.

(5) The keyboard, which is included for input and control of information to the computer, includes all characters available for display by the tube. Additional control push buttons are available. These are:

(a) Logic Power On-Off

(b) CRT Power On-Off

(c) Emergency Test Stopped (light only: controlled by computer)

(d) Display Busy (light only)

(e) Erase

(f) Keyboard

(g) Error (light only)

(h) Computer Request

(i) Keyboard Self-Check

(j) Keyboard Edit

Normal operating controls, such as focus, etc. are provided for the tube but are hidden during normal operation.

(6) The construction is such that the display can be a complete item and the keyboard with the associated controls can be deleted if desired.

(7) The input-output logic contained in the logic cabinet is sufficient to operate six display consoles. This common logic rack is one of the major features of this display design.

(8) The input-output via the keyboard is as flexible as possible. The operator can display or change the contents of any core location. The function is completely under the control of the RCA-110 program. The program to display or change information is selected by the proper control switches and keyboard code number, and the operator is limited only by this program.

(9) An indentification card reader is provided to allow only authorized personnel to operate the display device.

(10) The display uses, wherever possible, solid-state electronics that are "off-the-shelf." All printed circuit modules are of the RCA-110 configuration except for special purpose modules that might be encountered in power supplies, etc.

(11) The design and layout of the console use standard packaging techniques and allow easy access to all components. The cabinet that houses the power supplies and input-output circuitry is of the same external configuration as the RCA-110 computer cabinet.

The display system just described is one of the principal methods for operator on-line communication with the computer system. It provides the

means to request data from the computer, display the data in a tabular or graphic form, and allow the qualified operator to edit or correct data and insert it into the computer for processing. Provisions are made so that the display system will operate through the computer IODC. Each operational area will be furnished at least one display console. An example of these areas is:

a. Guidance System

b. Network System

c. Control System

d. Stabilizer System

e. Test Conductor

f. Computer System

g. Control Room

Computer attention is attained through external, automatic priority interrupt. Priority assignment of display consoles is accomplished by internal program priority methods. In the early phases of the automation plan and prior to the development of adequate programs, the test conductor will be used as a traffic controller of display-computer activity. The test conductor and several other display areas can eavesdrop on any other display presentation.

4. DATA LINK

The life line between the computer on the launcher and the one within the launch control center is the data link. A data link terminal is located at each computer complex, and each data link terminal is serviced by an input-output data channel of the operational computer. The purpose of this system is to provide programable communication between two RCA-110 computer systems, which may be as much as seven miles apart. Two classes of information may be transferred between the two systems.

a. Data (experimental results or programs)

b. Commands (requests and acknowledgments that tests be run, data be transferred, etc.)

Some of the significant system parameters are:

a. Commands are full duplexed.

b. Data words are one-half duplexed.

c. Information is transmitted serially by computer word with complete error checking on each word.

d. Distance between terminals may range between 1,500 feet to seven miles.

e. The nominal effective information bit rate is 133,000 bits per second.

f. Gross transmission rate, with redundant bits is 250,000 bits per second.

g. Output rate of the transmitting link is determined by the receiving system.

h. Each terminal has simulating circuitry that can be used for self-checking purposes in a disconnect mode.

In normal operation the data link terminal differentiates between command words and data words from the computer input-output data channel and generates a word identification for each word that is transmitted. The receiving data link terminal will recognize the word by its word identification and transfer it to the appropriate input-output data channel register (buffer register for data and status register for commands). When no information is available from the input-output data channel, the data link transmits sync words. A sync word is a pattern of all "zeros."

Error detection and correction is provided such that retransmission of a word will occur if (1) a transfer parity error is incurred during transfer of a word from the IODC to the data link transmitter, (2) the word indentification, as recognized by the data link receiver, is not legitimate, or (3) the receiver detects an error in the two-dimensional parity check. Information defining a retransmission request or the lack of such a request is transmitted with each word. Coding and error detection to provide a probability of an undetected error of 2.8×10^{-14} words/word are design goals.

The transmission method is synchronous phase shift key and the connection between terminals will be via armored twisted video cable.

Commands that can result in serious changes in vehicle state will not be executed by the launcher computer until a complete loop transmission is made of this command and verification from the originating computer is received.

II. PROGRAMING PLAN

Programing, as applied here, may be classified as two main areas, design and operational. In the design classification, there is required component, subsystem (more than one component operating together), and network verification. All of these programs exist solely to confirm that design requirements are met. Operational programs, on the other hand, are the application of design programing routines plus special facility type of functions arranged in an order to accomplish a given procedure.

Design programs are provided by the Astrionics Laboratory and consist of necessary routines to test and evaluate the design requirements of all Astrionics designed equipment. This area of responsibility includes all systems within the vehicle's instrument unit, ground support equipment, and contractor supplied electrical systems for which the Astrionics Laboratory has a launch site test and evaluation responsibility. Examples of these systems are:

A. Flight Guidance Computer and Signal Processor

B. Stabilized Platform (ST-124)

C. Control Computer

D. Azimuth Positioning System

E. Flight Telemetry System

F. Inverter and Power System

G. Emergency Detection System (EDS)

H. Radar Altimeter

I. Remote Automatic Calibration System (RACS)

J. Digital Data Acquisition System (DDAS)

K. Ground Equipment Test Sets

L. Stage Interface Test Sets

M. Countdown Clock

N. Network System

O. Stage Electrical Systems

All Astrionics-supplied programs that are furnished have the following characteristics:

A. Component Test Programs: All programs in this category are divided into subroutines which are the lowest level of control and verification. Each component test program can be initiated and performed in total. For diagnosis or other reasons, each subroutine can also be initiated and performed in total.

B. System Test Program: These programs, such as the navigation system, are composed of component test programs or subroutines arranged in a logical order so that the system in question is tested and evaluated.

C. Utility Programs: These programs are aids that enhance the effective utilization of furnished equipment test programs.

1. Hybrid Assembly Program (HAP) - An assembly program that runs on the IBM-7090 to produce object programs for the RCA-110 from a special language.

2. Symbolic Assembly Program (SLAP) - An assembly program that runs on the RCA-110 to produce object programs for the RCA-110 from a special language.

3. Diagnostic Programs - Programs that aid in the determination of valid computer system operation. These routines have been developed to function with an on-line operational system. In the area of input-output to the vehicle, the diagnostic routines require special considerations. We are presently considering a closed loop method in which the output lines not only go to the vehicle but also to the discrete activity indicator. With this arrangement, a rate of energizing can be utilized which will be sensed by the computer system but will not disturb the slower responding vehicle system. With this method, discrete input-output could be tested and verified during on-line operation.

4. Mathematical Programs - Standard methods of accomplishing machine-operated mathematical manipulation.

5. List Processor for Test and Checkout - An interpretive program which is a single pass, on-line statement processor. The language input to the processor is a collection of variable format, declarative statements composed of key words which may be operators, operands, or identifiers. Upon receipt of a statement, the processor will organize for execution a set of programed subroutines. Operands and identifiers will be inserted as subroutine arrangements. Following execution, a new statement will be accepted and the process repeated.

The format chosen for the list processor language was based upon the following considerations:

a. The statement should resemble the engineering statement as closely as possible.

b. The statement processor should not overburden the computer system.

c. The language must have sufficient flexibility for use as a common language in all installations responsible for vehicle assembly, test, and launch.

Some of the advantages gained through the utilization of a list processor of the type just described are:

a. Allows the test operator to write a machine program by transcribing his written procedures into a sequence of

statements using operators and source data in the list processor language.

b. Enables the man most qualified, the design and test engineer, to write much of the machine program.

c. Allows on-line program preparation and modification to be accomplished with a minimum of programer aid.

d. Unites all operational areas with a standardized program preparation procedure.

e. Provides a usable utility tool which is implemented with a minimum of training.

f. Provides standardized machine methods regardless of location.

The plan for operational program generation and control is:

a. Procedures Acquisition: A thorough survey is made and all procedures and drawings are acquired.

b. Language Program Generation: This process involves the use of procedures and requires the component designer, operational personnel, and program staff to discuss the problem at hand and establish a machine technique for accomplishing the task.

c. Flow Charting: The system's analyst and programer sit down and map out the computer technique and overall instruction flow to accomplish what is required by the detailed language program.

d. Coding and Program Debugging: This phase of program generation validates the initial flow chart and reveals areas which may require modification.

e. Systems Developmental Testing: This is formal testing within the Saturn Systems Developmental Facility to demonstrate the validity and continuity of the program. A review of equipment status before, during, and after testing as well as an evaluation of results is performed.

f. Program Authorization and Library Entry: The action of a valid test demonstration places the program in the authorized program library. Changes to this program must be reviewed and approved by all initial approving areas. The program library contains all items of documentation, which, if studied, reveals the logical step by step generation of the program.

g. Program Distribution: Each area that has a need for the program is supplied two copies plus explanatory documentation. If this program is replacing an existing one, then certification is required that the old program has been removed from computer memory as well as the sub-library.

III. OPERATING OBJECTIVES

A. Prelaunch and Postlaunch Checkout Capability

The discussion thus far has portrayed the automation effort which exists at the Marshall Space Flight Center relative to launch site operations activities. To be successful, this extensive program must operate with a vehicle system which is designed to enhance and support digital automated techniques. In the Saturn program, one of the major objectives is to provide a vehicle airborne system which is designed and implemented to complement the ground support equipment and to provide a complete and totally effective checkout situation for prelaunch and postlaunch activities. In this plan, primary onboard checkout systems include the onboard computer and data adapter, command receiver, digital data acquisition system, and remote automatic calibration system. Orbital checkout requires the onboard computer to perform as an extension of the ground checkout equipment under operational ground computer control. It performs closed loop tests, analyzes results, monitors important electrical signals, and communicates through telemetry channels to the ground support equipment.

B. Control Flexibility

In the application of automated systems, we are designing techniques that provide the flexibilities considered necessary for complete operator control over the automatic equipment. This requires the computer operational programs to be written to accept operator intervention at any time. Once intervention occurs, it may require the following action by the checkout system:

1. Perform an out of sequence test or report on past test results.

2. Stop the test presently being performed, delete the test, and continue in the main test sequence.

3. Stop the test presently being performed, sequence all necessary functions to allow entry at a test point previously performed, and enter the main test sequence at that point.

C. On-Line Program Modification

In any development program of checkout techniques, there is the requirement for methods that allow last minute, on-line procedure and data changes to be accomplished quickly, yet with confident accuracy. At the Marshall Space Flight Center, this challenge is being met with predetermined

and preprogramed routines which can be used or reassembled on-line by the test operator. Present experience with such a technique has proven the feasibility of this approach.

D. Increased System Reliability

The overall automation effort has as a prime goal the attainment of increased system reliability. To accomplish this requires:

1. Presentation of more accurate data because of automatic digital techniques.

2. Diminish vehicle system operating time during checkout and preflight activities.

3. Standardize checkout operations and provide qualitative and documented data which can be used for trend analysis.

4. Relieve system operators from time consuming tasks so they may concentrate on the more important analytical aspects of launch-site operations.

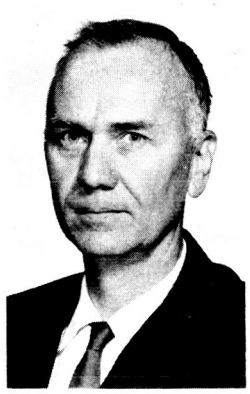
CONCLUSIONS

The automation of launch site operations is being implemented in a sequential order and schedule which allows a gradual built-up of proven techniques for the Saturn V vehicle program. This process provides adequate learning time for design and operations personnel to gain confidence in the hardware and concepts being employed.

It is recognized at Marshall Space Flight Center that automated digital technology is required to support large space vehicle checkout and control operations, but we intend to design and develop such techniques as a tool for the test operator and not as a substitute for his skill and knowledge.

PRACTICALITIES IN AUTOMATED MANUFACTURING CHECKOUT

Robert L. Smith, Jr.



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PRACTICALITIES IN AUTOMATED MANUFACTURING CHECKOUT

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INTRODUCTION

A little over two years ago, Marshall Space Flight Center (MSFC) decided that the Saturn space vehicle checkout and launch programs should be automated by using digital computers for remote control and evaluation. This was a logical follow-on to programs which had been in existence about a year and a half at that time. One of these programs was the development of a computer controlled system for launch of the Saturn I. The other was the development of a system for automated manufacturing checkout of the Saturn I first stage at Marshall. These two programs had indicated that although there were many unanswered questions, it was both feasible and desirable to establish an automated checkout and launch for all Saturn vehicles.

Today there still are unanswered questions. However, through the efforts of four major stage contractors in the Saturn program, and the overall coordination of MSFC, many answers have been found, and many standardizations have been set forth. This paper will present a number of these solutions and standardizations, which I have chosen to call practicalities. It will also point to some others that are yet to be established. The paper to follow this one in the symposium will then pinpoint development items that are needed to allow us to automate more fully than we are able to do today.

PROGRAM SUMMARY

With the exception of the S-IV stage, the second stage of the Saturn I vehicle, all manufacturing checkout for Saturn stages today is either being controlled by computers, or, when checkout first begins, will be controlled by computers. (Chart I shows these stages and the computers used.)

The last S-I stages to be built at MSFC are under construction at the present time. This is the first stage for both the Saturn I and IB programs. Mechanical systems checkout is partially automated under computer control; electrical and electromechanical systems tests are almost entirely under computer control, and have been for approximately ten months, with highly satisfactory results. Effort is continuing to improve techniques and extend control further. Manufacture of this stage is now beginning at the Michoud plant in New Orleans; stage checkout there will repeat the pattern at MSFC. Checkout of this stage is the only instance in the Saturn program where a multiple computer complex is used.

As previously indicated the S-IV stage checkout is not automated. Although manufacture of this stage began well after manufacture of the S-I stage, the S-IV stage checkout was not previously performed at MSFC. As a result, there was no previous attempt to automate, and none will be made in the foreseeable future.

The Instrument Unit of the Saturn I, IB, and V vehicles is somewhat different for each vehicle; it contains the guidance and most of the tracking systems. These units are treated as stages, and are built and checked out at MSFC using the launch site computer. Neither of the computers used in the Saturn I or Saturn IB programs will be the launch site computer. All equipment for use at the launch site will be designed and supplied by MSFC.

In the Saturn V vehicle, there are three stages. The S-IC stage, to be built in New Orleans, will be checked out using the launch site computer. The stage will be mounted immediately upon the Launch Umbilical Transporter upon arrival at the launch site. Since the base of the transporter will already contain the MSFC-provided launch site computer and other launch equipment, this equipment will be used for immediate checkout of the S-IC. The Marshall automation program requires that checkout of individual stages at the launch site be as nearly like manufacturing checkout as feasible, considering the difference in facilities and geographical location. Therefore, manufacturing checkout of the S-IC uses the launch site computer.

The second stage of the Saturn V, the S-II, will undergo manufacturing checkout in California, utilizing the same computer for control and evaluation as the S-IVB stage. When these two stages arrive at the launch site, they will undergo checkout as individual stages, utilizing basically the same equipment as that provided for manufacturing checkout. Basic knowledge gained during the manufacture of the S-IV stage was used to create a stage which is larger and quite different from the S-IV stage. This is the S-IVB stage, originally intended for use only as the Saturn V third stage. Since the Saturn V program required that manufacturing checkout for all stages be under computer control, the S-IVB was included. It will undergo checkout under computer control, therefore, even when built to be the Saturn IB vehicle second stage.

STANDARD APPROACHES

Computers: In a program as complex as the Saturn program, it is most desirable, as long as capability and flexibility are maintained, to use completely standard equipment insofar as possible. This is particularly true in the case of computers for stage checkout. However, certain practical considerations dictated that not all stage checkout computers be exactly the same.

The previously existing S-I stage programs had provided a wealth of background experience and development. Checkout of the S-I stage, therefore, has continued with the same checkout system. It has several individual test stations controlled by a central computer complex which includes

several Packard Bell 250 computers. The individual test stations are a grouping of stage interface equipment peculiar to particular stage subsystems.

The reason for choosing the RCA 110 launch site computer for the S-IC stage has already been indicated. It was possible to take a new approach with the S-II and S-IVB since these stages were under development at the time the computer was chosen. A computer was chosen which was later state-of-the-art, and which had more built-in features than previous ones. This computer, the Control Data 924, had inherent limitations with regard to input-output capability. When these limitations were discussed with the computer manufacturer, he proposed a modification to overcome the difficulties by providing buffered input-output registers. This resulted in the 924-A version of this particular computer.

We who have used computers in stage checkout realize that all things cannot be done with computers. To assume that a computer is a magic wand, rather than a complex, flexible, and advanced tool for stage checkout, would be a serious mistake. Unfortunately, this mistake is made by too many management people.

Since the use of computers for stage checkout is comparatively new, test procedures controlled by computers are quite similar to manual checkout procedures. Consider the following example however, to see improvements gained by the use of computers.

> A particular test on the Saturn I stage requires gimballing the rocket engines individually in increments of a few degrees and reading the static position feedback voltage at each position. Since there are a large number of steps for each engine involved, and a total of four engines to be tested, the entire test normally took, using manual equipment, about two and a half days. This allowed one reading per step and data was manually reduced. Approximately twenty steps gave twenty pieces of data per engine. When computer controlled stage checkout began, the entire test was finished in a few hours. Performance of the test took less than an hour. Additionally, thirty data points were taken at each engine position and averaged to obtain the best value for that position. Instead of twenty data points per engine, six hundred were obtained. If the test is rerun, it is certain that it will be repeated exactly as before.

Displays: Display of information during stage checkout is of particular importance at this stage of our steps toward automation. Each stage is somewhat different from other stages; different information requirements therefore exist during checkout. Further, information to be displayed is determined, to some extent at least, by the type organization doing the stage checkout. MSFC requires that information be presented to the test operators so that it may be read and interpreted in familiar terms and so that operators may judge the test and develop a "feel" for the operation. Except for certain special situations, this obviously precludes the presentation of checkout data in such forms as binary or octal code. The

checkout equipment proposal of each stage contractor is reviewed carefully and in detail by MSFC to determine that the information presentation capability is both sufficient and satisfactory.

Two types of information display equipment are being provided: standard items such as lights, meters, and in-line indicators; and cathode-ray tube (CRT) displays. (See Figure 1.) Almost everyone who deals with the general problem of stage checkout using computers believes that CRT displays, generally in alphanumeric form, are desirable. This may be more a matter of experienced engineering judgement than a particular knowledge or expectation of many individual things to be presented on the displays. Great inherent flexibility exists in the combination of a CRT display and the programming capability of a computer.

Those who propose to use CRT displays think in the direction of what can be presented, and what the display is able to do. Little is said about what is mandatory for the checkout. This is true of experienced people both inside MSFC and among stage contractors. For this reason, the ground rule for the Saturn automation program on CRT displays is that they will exist, but will have limited initial use. The three Saturn V contractors are pursuing slightly different approaches with displays in their own programs. Effort has been limited, however, to allow each stage contractor to develop and build a single display which will be used in his mockup facilities. He will test the entire stage mockup together with its automated ground support equipment. When all displays have been demonstrated and used, determination will be made as to whether such a display is needed at all, and, if so, which is the best approach. It will then be possible to apply that single approach to all stages.

Ground Equipment Testing: Experience at Marshall has indicated that it is essential that a complex of stage checkout equipment be tested after installation as it is assembled and mated with the local facilities, but before the stage is connected. This will be done using a Ground Equipment Test Set. The Ground Equipment Test Set is a comparatively simple device, basically manual in operation, which serves as a stage interface substitute for use with the stage checkout equipment. It consists mostly of relays, lights, and patch boards, and has allowed for satisfactory checkout of an automated complex. Its simplicity and use of common equipment keeps the cost of such a device quite low and makes it additionally attractive. Doubtless, much more elaborate and complicated equipment could be used to do the same job. The simple approach, however, proved to be definitely acceptable and by far the least expensive.

Data Acquisition: In order to provide improved information transfer from the Saturn V vehicle, it was decided some time ago that Pulse Code Modulated (PCM) telemetry would be utilized. Consideration of stage checkout caused a further decision to extend the system to allow information to be brought out from the stage on a coaxial cable through the umbilical connectors. This permits a more complete evaluation of the instrumentation system of the stage, particularly during launch pad operations, than was previously possible. This approach utilizes the front end of the PCM

telemetry system, and is called the Digital Data Acquisition System (DDAS). The design approach to the airborne and ground equipment for this system has been standardized, and established by Marshall as policy for the Saturn V. (See Figure 2.)

Proper calibration of the flight instrumentation system, to insure the best in accuracy and completeness of information, requires more elaboration in performing instrumentation checkout than most organizations are willing to give. Use of the DDAS allows for this necessary elaboration of testing without requiring extra connection of test equipment into the stage. Further, provision is made in the airborne instrumentation system that, during a semi-static situation such as a stage checkout, information from other telemetry systems can be transferred to the ground by means of the DDAS, where the response in this semi-static condition is within the capability of the DDAS.

It was originally expected that the DDAS would provide much information for evaluating stage checkout, even though each instrumentation transducer to be used as a data source for stage checkout must be calibrated prior to checkout use. Recent studies have indicated that reliance upon data from flight transducers is minor at the present time. Whether this is because a previous calibration cycle is necessary, or because of the present difficulty of accessing stage information has not yet been determined. Where orbital checkout is necessary, reliance on flight transducer information is essential. At this time, however, it is not possible to accurately predict whether the DDAS will merely enhance the calibration of the flight instrumentation (which is saying a lot in itself), or whether, in addition to that, it will greatly aid access of information for stage checkout.

Discrete Signals: Much information that is used for evaluating stage status during checkout is derived from discrete, on-off type signals. This alone indicates that use of the Digital Data Acquisition System will not be as extensive as previously thought. Nevertheless, the problem of accessing, recording, and evaluating the discrete or event signals is a major and a serious one. Almost everyone in the missile and space industry relies today on drag-pen recorders which change level in some fashion to indicate an "on" or an "off" condition. When recording five hundred to one thousand discrete channels is required, especially during a launch, the problem of evaluating these recordings becomes monumental.

Several years ago, it was realized at Marshall that this problem was becoming more severe, and that it would be desirable to have a device which could digitally record channel number, whether the event switched "on" or "off," and the specific switching time. A market survey was conducted, and no such device was found. Therefore, specifications were written to allow for development of such a device. Results of the initial development proved highly satisfactory in use. Unfortunately, the device itself was unreliable, and therefore, a second effort is currently underway.

Much thought has been given to providing the capability for event recording within the checkout computer itself. However, the record must,

in general, be accurate to about two milliseconds; five hundred to one thousand channels of information are necessary for a major stage checkout; during certain periods major events occur, such as simulation of lift-off, which produce a number of simultaneous changes of state.

Discrete recording alone would occupy almost the entire time of the checkout computer. Requirements for one or two millisecond resolutions and absorbing simultaneous changes of state make this development most difficult. Present direction to stage contractors, therefore, is that drag-pen recorders will continue to be used for event recording until a device has been developed and proven by Marshall for this use. Instructions will then be given to stage contractors to change to the new device.

The use of a digital event recorder will greatly aid in recording of running or cycle time on flight-critical hardware, since switching for this hardware can easily be incorporated into event channels. Further, if access to the computer for off-line updating of time information is provided, either through direct cabling or through use of magnetic or punched paper tape, evaluation, updating of historical records, and other valuable information processes will be simplified considerably.

Initial Operations: As previously explained, in the beginning automated checkout procedures and operations will closely resemble manual operations. This was true in the initial programming and operation of the S-I stage automated checkout at Marshall. The enormous capability and flexibility of computers, however, provide the ability to go well beyond this. It may be confidently expected that this extended use will proceed at a rapid rate, once test organizations have begun to use computers. A standard requirement of the Saturn automation plan is that the operator be provided controls and displays that are nearly as flexible as in a manual system. It is fully intended, however, that the computer be in control of both stimuli and evaluation of responses.

For example, requirements have been incorporated for what has been called "local control." This allows the operator, upon receipt of a manually switched "permission" from the test conductor, to control his stage interface equipment locally. By manipulating switches, he follows the same control route within the test station as the computer. He may accomplish nearly anything of which that particular test station is capable. The intent is to fully automate, and yet, at the same time, provide sufficient flexibility that test organizations can retain a great deal of confidence in their flexibility and capability to react to emergencies.

Mockups: A further standard approach to automating of the Saturn V stage checkout has been to allow each stage contractor to provide or have access to a mockup facility. This includes a mockup of his stage, and an actual installation of all his electrical stage checkout equipment. The extent to which the mechanical stage checkout equipment exists in the mockup is determined, to some considerable extent, by the elaborateness of the stage mockup. Reproduction of much of the propellant-sequencing mechanical system in the stage mockup is desirable. This allows proving

the performance of the automated system with the stage system, and further permits solution of those built-in timing problems which cannot be foreseen but which, particularly in a computer operation, must be covered.

For example, during automated instrumentation calibration of the S-I stage, the stimulus applied by the computer caused a periodic change in transducer conditions, requiring a settling-out time before a reading of the return signal could be taken by the computer. If the reading was taken prior to the settling-out period, the value was incorrect in almost every instance. The computer speed is high, and the computer is quite capable of taking the reading too soon.

Proving-out of stage checkout procedures is also possible and desirable before stage checkout begins. It is not absolutely essential, as long as considerable care is taken with the first live stage checkout. No mockup facility for the S-I stage or its automated stage checkout equipment existed; the first real proof of operation of the equipment took place on a flight stage. A mockup facility, however, provides a very good insurance policy.

WHAT TO LOOK FOR IN A COMPUTER

A test operator performs many actions without consciously thinking of them. For example, when the power supply is switched on, a quick glance at the meters indicates that the voltage has risen to the proper value. If so, the test proceeds. If not, corrective action is taken before proceeding with the test. This is true of many steps within any test procedure. The English-language version of the test procedure need not call this out, because the operator has done it many times and knows what to do without thinking. Unfortunately, a computer does not think. Therefore, the test engineer must provide all necessary thinking for the computer in advance. In many respects this is good, because it forces him to think through troublesome situations before they arise. He then builds a provision into the computer program for an alternate routine in case of anticipated difficulties or symptoms. The problem can then be solved, or at least isolated, by the alternate routine. To provide this in a language useful to the computer, however, is a different problem. For one thing, the language which the computer speaks is extremely precise. This, to say the least, is not true of the language which the test people speak. Nevertheless having worked together for some time, they can communicate with reasonable effectiveness, although their wording is not, perhaps, as exact as it might be. Conversion, then, of the actual thoughts of the test planner must be performed so that the machine can do its job properly. The easier this conversion can be made, the more likely the job is to be done properly.

Besides the conversion, there are operations which are sometimes more than just iterative and/or just series operations. They could become complex, even when carried out manually. Some tasks which must be accomplished with equipment which is, in effect, in parallel with the automated equipment, so that one part of the task is accomplished manually while another part is accomplished automatically. Any one of these things could

cause difficulties. When one must consider all of them together, which is true in every stage checkout, then ease of computer programming becomes a primary consideration. Computer commands which accomplish a multiple function are important because of saving computer steps. A single command, for example, to allow a readout and a high-low comparison would be preferable to a requirement for a command for the readout, a second command for the high, and a third command for the low comparison. Further discussion of programming will follow in a subsequent paragraph.

System Control: Another important consideration for a checkout computer might be called "fingers into the system." Even a fast computer which consumes much time in information transfer into and out of the machine, is inherently limited in control or supervision of a system. In a space vehicle stage checkout, many things occur simultaneously, particularly during simulation of the flight sequence; commands must be given rapidly and readings taken quickly. The computer for stage checkout should have as many paths as reasonably possible into the control of the system itself. The total number of paths probably could be specified for any particular task, and then built into a single machine; but what is optimum for one situation is not for another. Marshall experience has indicated that a single path is definitely not satisfactory. Three, to perhaps as many as ten or twelve, would be the optimum number of paths for a control computer for stage checkout.

Simultaniety: A further desirable feature, and one which ties in almost directly with the previous paragraph, is that capability of the computer which is generally referred to as simultaneous read/write/compute. The checkout computer should utilize a small percentage of its time to bring in or send out information. A benefit realized during stage checkout from this capability is ability to control and manage several systems, or several parts of the same system, simultaneously. A computer with comparatively few paths into the system can gain, effectively, additional paths through having simultaneous read/write/compute capability.

Memory: Much can, and has no doubt, been said with regard to the memory of computers. Work is continually going forward to improve computer memories, to reduce their size, and to do other things which would optimize them. There are three outstanding features which should be considered in terms of memory for a checkout computer. Considering further the discussions in the previous two paragraphs, that computer memory which is most immediately and directly accessible is that which is the most useful. The memory operation is for the ultimate purposes of system operation, and is one which might be considered "overhead." Memory accessibility, therefore, is the first important memory feature.

A second important memory feature is that it be permanent. Frequently during a stage checkout, situations arise which require a quick switch-down of power, or which, perhaps, blow major breakers in the electrical system and cause power to be lost. In bringing power back on to the system, great care must be taken to see that all things are in proper order so that

the stage is not damaged or destroyed. A computer which has a memory which can "lose its mind" upon loss of power, can make this situation very much worse.

The third important memory feature of a checkout computer is size. This feature is almost inseparable from ease of programming. The memory capacity of a checkout computer must be able to hold necessary executive routines, trouble-shooting or other types of subroutines, and to hold the test to be performed and that data derived from it and used in it. The more auxillary equipment external to the computer which is used, such as cathode-ray tube displays, line printers, magnetic tape transports, and typewriters the more memory is required to manipulate these devices.

Speed: Considerable emphasis has been given to the speed of computers. In a checkout computer, speed has considerably more significance than just a reference to the clock-rate of the computer. There is always a problem of how much electro-magnetic interference can creep into any system which is as diverse and as scattered as the checkout system for a stage. This becomes more true when digital signals and digital speeds are involved. Therefore, as the clock rate of the computer goes up, one could expect more difficulties with checkout computers. A clock-rate of approximately two megacycles has not yet offered much difficulty.

In most cases, the computer will be sufficiently fast that it is waiting on the stage system under test. The stage system, being mostly an electro-mechanical system, is naturally much slower than a computer. On the other hand, if event recording within the computer is attempted in addition to all other things, the point of external-to-internal power transfer or simulated lift-off causes many discrete events to occur simultaneously. The speed of the computer then becomes extremely important in the terms of the clock-rate. This is worse still when calculations must be performed or detection of a certain event within a particular time frame is necessary for sequencing. Speed in a checkout computer, therefore, is closely interwoven with ease of programming, paths for system control, simultaneous read/write/compute, and memory access time. It is additionally affected by the magnitude of the task to be done internally, as opposed to the external tasks, such as event recording, provision for external equipment to have internal storage, signaling, refresh rates (in the case of displays), and so on. Speed must be a rather fine balance between, not only the capability of the computer and its clock-rate, but the expected environment in which the computer is to operate with regard to electro-magnetic interference and external equipment capability. A new system design can obviously provide more external capability than an old one upon which a computer is superimposed for control.

Reliability: Certainly a major factor in a checkout computer is reliability. In terms of stage checkout, reliability also tends to acquire a different meaning from that for a computer in other applications. In the first place, space vehicle programs are low-volume, high-complexity programs. Until space technology evolves into a true transportation system similar to the airline systems, space programs will be operated by highly

skilled, technically trained people. In this situation, those who are using the computer or who are benefiting from its use are technically skilled and are therefore capable of taking into account, not only the intricacies of the computer itself, but perhaps also its reliability quirks. Further, a daily self-check program, to any necessary level, can be performed on the computer to establish that it is operating reliably. Experience will indicate the time that continued reliable operation can be expected. Experience with stage checkout computers at Marshall Space Flight Center has indicated excellent reliability.

The greatest fear of the checkout man who has not used automated equipment previously is that something will happen to this equipment during a test to cause an emergency condition which he cannot control. The precautions which one usually takes with any type of checkout equipment are the type precautions to take with computers in checkout. The results, in terms of reliable operation during a particular test, are quite satisfactory. Manual stage checkout equipment which has been used for many years is equally susceptible to having emergency fault conditions cause a checkout crisis. Computers are assembled with printed circuit cards, generally of silicon, and are very regularly checked for proper operation. The frightening part of computer use to the checkout man is, first, that he is, generally speaking, not as acquainted with computers as with previously used equipment and, therefore, does not know what to expect; and second, a computer appears to be at least somewhat more complex than the equipment he normally uses. Once again, he does not know what to expect. His real fear, therefore, is of the unknown, rather than fear of something which could happen to him with computers but not under his present circumstances.

THE "INTERFACING" APPROACH TO STAGE CHECKOUT

It appeared some time ago to be desirable to have equipment for checkout of individual stage subsystems at a single location and within a single group of cabinets. This single group should be all necessary equipment for a subsystem. Subsequent experience has indicated that a somewhat different approach will probably give, in many cases, more desirable results. This approach I have called the "interfacing" approach to stage checkout. This term simply means to consider all interfaces needed for the stage checkout equipment and design for interfaces rather than equipment grouping. (See Figure 3.)

In an automated checkout, there is a stage to be checked out and a computer to control and monitor this checkout process. All equipment used other than stage and computer is defined as stage checkout equipment. The stage checkout equipment, therefore, interfaces in three ways: with the man who is monitoring the checkout, with the stage, and with the computer. In the original concept, all three of these interfaces for a given subsystem were a single physical group of equipment mounted in a single physical group of cabinets. This concentration is not essential as long as each of the three interfaces is provided for each stage subsystem. The stage interface equipment, however, for a particular subsystem should be grouped within a single group of cabinets physically located adjacent to one another, insofar as possible. This will simplify trouble-shooting greatly. This is a

natural result of good design in most cases. Let us then attempt to determine those things which are practical with regard to these interfaces.

The Stage: First consider the stage interface. Stage design has evolved from a series of compromises, beginning with the mission of the flight of the entire space vehicle. The mission has caused decisions for optimum staging, and these have determined how many stages must be used. The number-of-stages decision has then bracketed the nature of each stage. Definition of individual stages and the entire vehicle have determined a pattern for how the vehicle will be launched. Design of individual stages can then progress, based on the determination of what a particular stage must be like, and how it must be handled during the launch operation.

Manufacturing checkout must determine, among other things, that the stage will mate properly with launch site equipment. Manufacturing checkout equipment then must be determined by launch considerations and by the individual stage itself. Some things aboard the stage will be designed in a manner to facilitate utilization of digital equipment; other things will be designed along the older and more conventional patterns, and use of digital equipment for these will require some type of conversion. Launch considerations will further determine types of stimuli to be put into and received from the stage umbilical connectors. The pattern for the stage checkout equipment interface with the stage is then established, based upon all of the listed considerations.

In many cases the most desirable provision for performing a stage test will not be built-in aboard the stage, because a compromise has been necessary in the stage due to weight, environmental conditions, safety considerations, or other things. The stage checkout equipment which interfaces with the stage will be an aggregation of some digital systems and some analog equipment. All of this will interface with the stage through the stage umbilicals, and, since we are speaking of manufacturing checkout, through other test connections.

Use of test connections other than normal stage umbilicals may meet with some disagreement. It would be more desirable in all checkout to connect the stage umbilicals as for a launch. The capability for this, however, will be determined almost entirely by what checkout provisions are designed into the stage. If full capability for accomplishing manufacturing checkout were designed into the stage, umbilical-only connecting would be possible. Even then, however, one would have to consider mating with the other stages. Proof of mating capability requires a connection at the forward and aft end of the stage to some device which simulates the interface between the stage under test and the adjacent stages. Since the purpose of this paper is not to discuss in detail the desirabilities for doing a proper stage checkout, let it suffice to say that we will assume that connections other than umbilical connections are necessary.

The Computer: Inherent capabilities of the checkout computer determine much of what must exist in the stage checkout equipment. Those checkout capabilities required which cannot be supplied by an overloaded or inadequate computer must be supplied in the stage checkout equipment. What

is supplied there will reflect directly into the interface of this equipment with the computer. An additional consideration is what information must be presented to and commands taken from the man controlling the testing.

A simplification of the computer interface may be obtained by building the stage checkout equipment with basic digital hardware, such as printed circuit cards and so on, obtained from the computer manufacturer. This can eliminate logic level conversions, word structure conversions, and other like things. However, equipment previously used by the stage manufacturer on other programs may already be available and require minimum modification for use in the current effort. These, and other considerations such as schedule time and cost may well dictate a practical engineering compromise to use available hardware, even though it does not match directly with the chosen computer.

As a general consideration then, it is safe to assume that a computer interface device, to be connected between the computer and stage checkout equipment, and to provide necessary conversion, will be used. This compromise, however, provides a happy side benefit: Exchange of the interface device, as appropriate, allows different computers to be used in other locations if necessary, as long as the minimum computer capability required in the original design is supplied. This does not negate the fact that it is always more desirable to have manufacturing checkout resemble launch site operation as nearly as possible to insure a successful launch operation. It does, however, offer an approach which permits other considerations.

The Man: The degree of human participation, in any individual case, will determine the nature of the interface between the man and the stage checkout equipment. This interface looks in two directions for control and information: toward the stage checkout equipment, and toward the computer. As previously indicated, present experience of checkout people with automated, digitized equipment is very slim. Therefore, computer contolled stage checkout today is quite similar to manual operations. In the man interface there is much display equipment, in particular such things as in-line readouts, lights for discrete indications, cathode-ray tube displays, and other sources of visual information. It also provides for taking over test control under certain circumstances, in particular those which are concerned with safety. Direction to Saturn stage contractors has been along conservative lines. Hard wire connections are provided for safing functions, with positive, manual, over-riding initiation. In all tests, provision for trouble-detecting and trouble-correcting subroutines will be made within the computer. If indications are received that an unsafe condition is about to occur, the computer will jump to a subroutine to save the stage. In most cases, the speed of the computer will have the stage in a safe condition before the operator recognizes that an unsafe condition has existed. Regardless of this, however, it is necessary to provide, first, for the possibility that the unsafe condition may not have been conceived previously, and therefore allowed for in the computer programing, and second, that some item of digital equipment will fail and that the human can intervene to save the stage. Even if the

manual safing equipment is never actually used, it provides that extra margin of confidence for operator assurance that his system is completely under his control.

Those things which are true of safety are no doubt true of other controls and readouts which appear, at the present time, on the man interface to the system. That is, whatever is provided in the computer program in the way of stimuli, recognition of sequencing, evaluation of data, and so on, will probably be handled more quickly and more efficiently by the computer, and at such a speed that the human will only recognize after-the-fact that it has been handled. This is clear from Saturn automated testing already under way. Further, as anyone knows who has conducted tests on large stages, there is a certain "feel" about a test which, after the test has run, allows the operator to judge its relative success. This "feel" is developed through a number of things, including glances at individual instruments, patterns of light indications, general sounds of the test as it progresses, and so on. A test performed in complete isolation, with no indications, meters, or sounds, would delete this capability. Although it is inexact, and certainly not subject to hard engineering scrutiny, the experienced operator recognizes this valuable tool for addition to the concrete data for test evaluation. This is more particularly true when a test is not satisfactory; the "feel" of the operator can then guide the trouble-shooting activity.

In beginning to automate a stage checkout, therefore, experience indicates that definite provisions should be made for operator control, operator override, and operator information reception. These, in turn, build operator confidence so that he begins to place more trust in this new and highly complex test device, the computer, because he can see with his own eyes that it is actually doing its job properly. Having this confidence, he then will begin to devise new means of using it, and as a result will move more toward full use of the capability of the computer.

External Equipment: The general tendency with Saturn automation has been to attempt to have external devices which can stand on their own. For example, in cathode-ray tube displays, such things as automatic refresh, internal storage, internal character generation, and so on, are almost essentials. As computer use increases, and as use of the capability of computers increases, as it will do when people become accustomed to them, external capability will become even more important than at present. Tests will be combined, so that several of today's tests will be run as a single sequence. The more that is to be accomplished in any single test or test procedure, the more capability is required, given a specific computer.

PROGRAMMING FOR CHECKOUT

One of the areas which has caused a great amount of concern in providing automated stage checkout has been how to provide necessary computer programs so the computer does its job properly, and to insure that it does not fail to do necessary things, particularly in the case of an emergency situation. Much of this concern, no doubt, has been the result

of a lack of understanding as to exactly what was involved in computer programming and the capability of this programming by people who have had a good knowledge of operational systems and flying stages. As computer use has increased, and particularly in industrial-control type applications, more and more engineers have received training which provided fundamental knowledge of computers and computer programs. This basic training, together with systems knowledge from experience, has aided greatly in establishing the fact that because a computer operates only with ones and zeros, it is not necessarily incapable of doing complex tasks in stage checkout. A gap, however, still exists between the computer programmer and the systems engineer responsible for a stage checkout. At present, it appears easier to train the programmer in systems, than it is to train the systems engineer in programming. Unfortunately, most automatic checkout programs are needed in a hurry. The necessary time-consuming cross training to insure good communication between the test engineer and the programmer simply is not possible. A basically different approach is needed to establish means whereby the thoughts of the test engineer can be translated most directly and placed into the computer program to do the checkout task properly.

Within the Saturn program there are three different computers being used. Presumably, for future programs a more advanced computer can be used, if available. If not, one of the present computers will, no doubt, continue to be used. In either case, a desirable feature for computer controlled checkout would be a single language which could be spoken by all persons concerned with checkout and operation of the computers, and in which all words and phrases would mean the same things to all people. Further, the problem of translation of this language into the language of the computer would then be greatly reduced.

A start toward the solution of this problem has been made at MSFC. A programming technique has been developed for sequential tests which requires only two computer programs to be written for each combination of computer and checkout equipment. The two programs may be considered to be translator operations.

The first step in writing a test procedure with this technique is for the test engineer to set down, on a standard form, the steps he wishes to accomplish, together with specific information concerning each step. This is then punched into cards, and the card deck is fed into the computer in an off-line operation. The first translator program is used in the computer to provide a conversion and produce a punched paper tape. It also produces a printed copy of the test which may be used by the test engineer for verification, and for following the test as it is performed. The second translator program is then loaded, and, in an on-line operation, the tape is played into the machine. The translator converts the tape steps directly into system actions.

This technique has been used for two different types of computers, using the exact same format for getting information from the test engineer. Obviously, variations to the procedure are possible. The significant advantage is the need to write only two computer programs for each combination of computer and stage checkout equipment. Once these are established as

correct, any number of tests may be written without further dependence on programming. Test modifications may be easily made ahead of time by exchanging cards in the deck before going through the first translator routine.

This type of programming has been used successfully with sequential tests where the next computer operation is dependent on receipt of a time-bracketed signal indicating that a previous operation has been successfully accomplished. It has not yet been possible to apply this approach in a completely satisfactory manner to the type of testing in which the procedures are largely iterative, as, for example, instrumentation calibration. Further work is being done with reasonable success in an attempt to extend this technique to make it more universal and, therefore, more useful. Obviously review of test procedures for correctness and sufficiency is made much easier by this method.

Once the two translator programs are established, they are fixed for the particular computer and set of equipment, and do not change. If it is established that these programs are correct, it is then only necessary to verify that the form which is filled out by the procedure writer or test engineer contains the necessary and sufficient information to perform the test as desired.

Another desirable feature for programming of computers for stage checkout is a technique within the programming method which will allow for ease of on-line change. During the time that a test is being performed it is frequently found that something is not performing properly, that some particular piece of flight hardware has been changed and the new hardware has different parameters, that the characteristics of some particular piece of flight hardware is different from a previous one, that some modification has been installed into the system since the program was written, and so on. Changes in the test procedure are then necessary to allow for these changed test conditions. Ease of change, therefore, under conditions when testing is imminent, must be one requirement of checkout programming. This, unfortunately, is not a requirement which has been solved as yet. It is therefore necessary to maintain the conservative approach indicated previously whereby the man interface has controls to allow him to handle unprogrammed situations. The type of programming just described probably comes as close to permitting this change as anything determined to date. However, even that type of programming requires first the filling out of a format, and then the feeding of punched cards into a computer in an off-line operation. Therefore, even this is not optimum. Change, however, should not be so easy that it is possible for an inexperienced operator to perform a few manipulations, and thus change the basic intent of the writer of the test procedure, or to place the stage into a dangerous condition.

In summary, a start has been made in programming for checkout using a single language which includes ease of translation, ease of review, ease of communication from engineer to computer, but does not yet provide for that very necessary ease of change in programming to accommodate unexpected situations during test.

CONCLUSIONS

Operation with automatic stage checkout under computer control for approximately a year, and consideration of the necessary means for doing this for various stages and under various conditions for several years, has indicated that there are a number of highly practical approaches which must be taken. Additionally, there are methods and approaches which are generally desirable but are not absolutely essential. There is no question that it has been well established through experience that automated checkout of a space vehicle stage, utilizing a computer for control and monitor of the results, is probably the most flexible and powerful thing that has happened to stage checkout since it first began. There are many projections which can be made as to utilizing the full capability of the computer in performing this task and improving the general state of the checkout art as it now exists. These are things which must be built on what we have already done and what we already know. The building must be practical and yet not reluctant, in a way that is forward looking, and yet is not extravagant, and in a way that allows us to maintain the gains which have made to date in space vehicle technology and the successes we have accomplished in space vehicle launchings. At the same time we must rapidly push forward the state-of-the-art such that we can have a successful space transportation system even as we now have a highly successful air transportation system.

CHART 1

MANUFACTURING CHECKOUT COMPUTERS
SATURN PROGRAM

	STAGE	COMPUTER	LOCATION
SATURN I	S-I	PB 250	HUNTSVILLE/NEW ORLEANS
	S-IV	-	-
	INST. UNIT	RCA 110	HUNTSVILLE
SATURN IB	S-IB	PB 250	NEW ORLEANS
	S-IVB	CDC 924A	HUNTINGTON BEACH
	INST. UNIT	RCA 110A	HUNTSVILLE
SATURN V	S-IC	RCA 110A	HUNTSVILLE/NEW ORLEANS
	S-II	CDC 924A	SEAL BEACH
	S-IVB	CDC 924A	HUNTINGTON BEACH
	INST. UNIT	RCA 110A	HUNTSVILLE

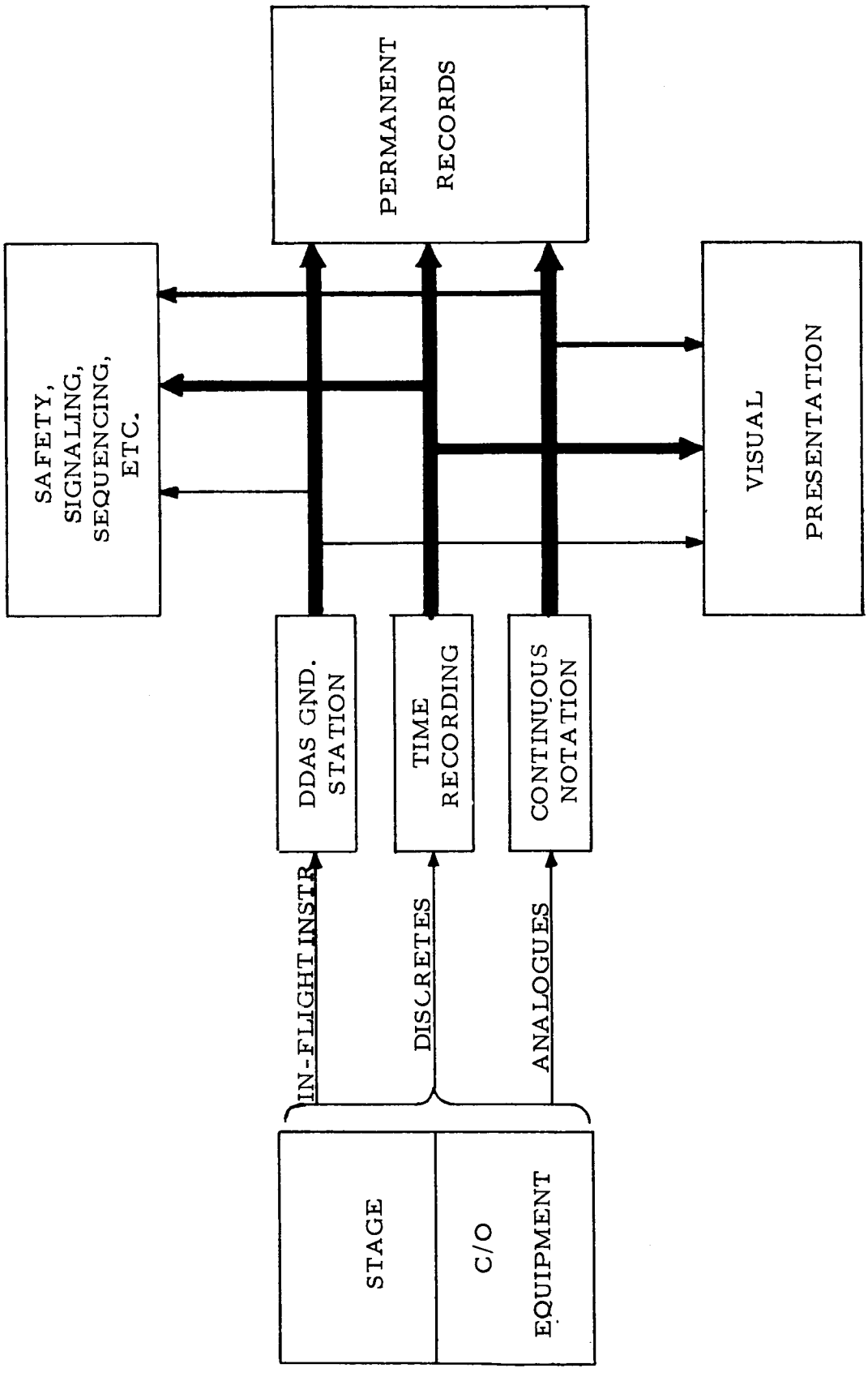

Figure 1. Information Flow in Stage Checkout

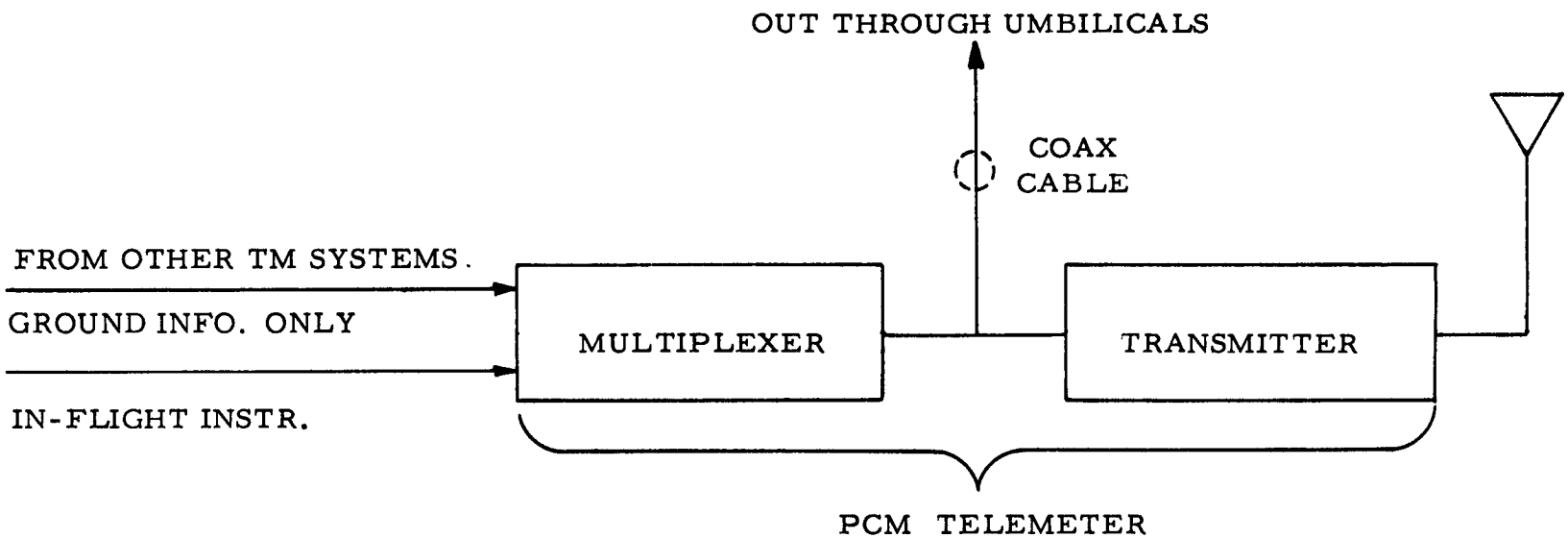

Figure 2. Information Flow in PCM/DDAS System

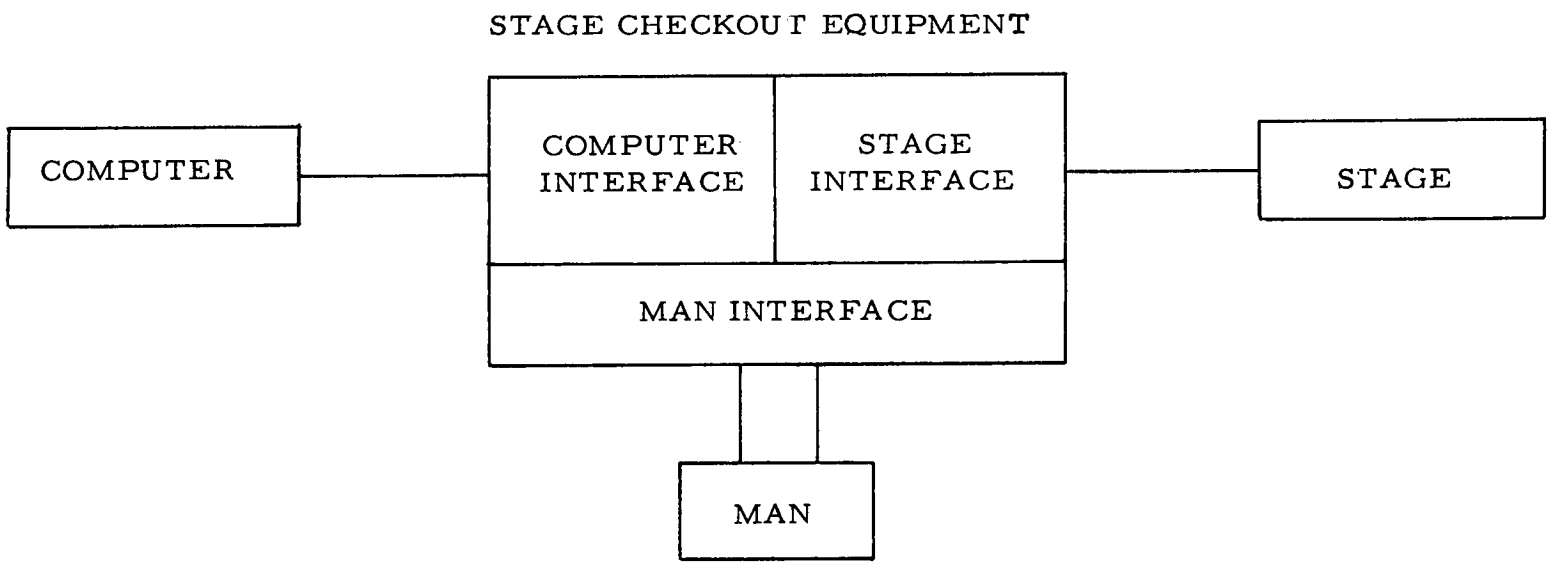

Figure 3. The Interfaces, and Signal Flow

FUTURE TEST AND CHECKOUT CONCEPTS FOR SPACE BOOSTER SYSTEMS

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Future Test and Checkout Concepts

for

Space Booster Systems

by

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October 1963

ABSTRACT

Major problems presently limiting the applicability of automatic checkout equipment to factory checkout of large space boosters are discussed. SATURN I instrumentation systems capabilities and factory checkout requirements are compared to establish the magnitude of the problem of vehicle evaluation using vehicle borne instrumentation.

Guidelines along which vehicle design and checkout techniques must evolve, to permit greater use of A. C. E. capabilities, are discussed. Representative programs in checkout techniques development at the George C. Marshall Space Flight Center are presented.

The paper concludes with a discussion of far future vehicle checkout systems characteristics and problem areas.

INTRODUCTION

The presentations given earlier in this morning's session have dealt primarily with the application of automatic test and checkout techniques and equipment to present space booster systems. In discussing future factory test and checkout systems, it will be more to our advantage to speak in terms of problems and their solution.

We are assuming that future space booster systems will still require checkout. We also assume that test and checkout operations will be performed at various times as the vehicle progresses from the manufacturing stage to completion of its mission.

These assumptions need to be noted, even though they may appear obvious, for two reasons. First, to establish the conditions under which this presentation is developed. Secondly, to permit acknowledgement of the fact that factory test and checkout operations have an ideal goal of eliminating themselves. Attempts to reach this goal are made by feedback of test and checkout findings to design and fabrication groups.

OBJECTIVES OF FACTORY TEST AND CHECKOUT OPERATIONS

The objective of factory test and checkout operations should be to assure that the vehicle system functions in accordance with design intent.

In order to reach this objective, the factory checkout operation must verify the proper functioning of all vehicle systems and subsystems. Verification of the proper functioning of a system or sub-system, without regard for whether the test is manual or automatic, requires some means of stimulating the test specimen and some response from the test specimen (Fig. 1). This response must contain sufficient information to permit evaluation of the status of the test specimen.

We encounter our first problem areas in the lack of a means of stimulating many vehicle sub-systems, and systems, and in a lack of having, or having available, responses of the subsystems etc. to automatic test and checkout equipment.

STIMULI GENERATION AND RESPONSE EVALUATION

Reviewing the results of flight firing operations of several large liquid propellant space booster systems shows a distribution of malfunctions, listed in table 1. The propellant pressurization, feed and engine systems, those systems responsible for about 45% of inflight malfunctions, are the systems least amenable to being stimulated by, and generating a meaningful response to, automatic checkout equipment. The guidance, control, and steering systems which were responsible for about 40% of the inflight malfunctions, are to a great extent amenable to automatic stimulation and do generate meaningful responses. Electrical networks and control systems, which were the least offenders, are the most amenable to automatic test and checkout.

Much work is required in the development of automatic test and checkout techniques and methods for mechanical systems. Future mechanical systems designs should attempt to provide a means of stimulating vehicle systems and subsystems automatically. In many instances, meaningful responses may not be obtainable using present techniques. New techniques, such as acoustical monitoring may be required (Fig. 2). Ideally these techniques should utilize passive instrumentation systems and should enable predictive analysis rather than diagnostic analysis.

FUTURE CHECKOUT SYSTEMS CONFIGURATIONS

Reviewing future mission requirements for large space vehicle systems shows ever-increasing operating time requirements for many systems. As these operating times increase to periods of years, (eg., Mars missions) the significance of the single checkout operations performed immediately after fabrication, decrease. Conversely, more and more information concerning system status will be required to be available on-board the vehicle.

Eventually, the vehicle system will contain sufficient stimuli generation and response evaluation to permit its own evaluation of its own status to such a degree of thoroughness that the operation might be suitable as a factory checkout operation.

The first step toward reaching this goal should be to make maximum use of on-board vehicle measurements for factory checkout. While many types of aircraft and missile systems may be amenable to this approach today, such is not the case with large liquid propelled booster systems.

Tables 2 and 3 summarize the accuracies of transferred measurements and percentage of transducer rejections presently encountered in SATURN I systems during factory test and checkout operations. It must be emphasized that these systems are more accurate than listed and more reliable than would be inferred from the rejection rates listed. These accuracies are guaranteed, and the high rejection rates are caused, by stringent factory checkout requirements. Nevertheless, if we are to talk of using these systems for factory test and checkout operations, we can only rely on the listed accuracies and we can count on having a large percentage of transducers off the vehicle in replace, rework or rejected status.

If we assume adequate accuracy and reliability of the vehicle measuring system is attained for factory checkout, we must now assure that the measuring transducers are placed in the proper location and have the proper range for factory use.

Table 4 summarizes the present problem. Less than 2% of vehicle transducers are located in the proper location to permit their use during factory checkout. We feel this condition might be significantly improved in the future by replacing developmental measuring programs with checkout measuring programs as

confidence in the vehicle design adequacy increases. Further, specific effort can be made by test and checkout personnel to arrange test criteria to be more easily used with vehicle borne instrumentation.

AUTOMATION OF CHECKOUT ENGINEERING INFORMATION SYSTEMS

The performance of a large space booster checkout operation depends entirely upon some group of engineers and technicians for its definition. This group must interpret large amounts of engineering documentation in order to develop test procedures, equipment designs, test plans, test instructions, etc. This situation is presented in Fig. 3. There are many sources of possible error and much unavoidable duplication of interpretive work apparent in this process today.

A feasibility study is presently underway, at the Quality Assurance and Reliability Laboratory of the George C. Marshall Space Flight Center, to determine if these error sources can be minimized or eliminated. The use of computer systems to supplement the checkout operations process (Fig. 4) in areas of engineering analysis prior to the test and checkout operation should not be considered as straightforward ADPS problems.

The system being studied is based upon a functional notation methodology developed by NASA and described in NASA Technical Note D-782. A sample system "Sequence Diagram" is shown in Fig. 5. and an equivalent system schematic is shown in Fig. 6. A detailed discussion of the notation is beyond the scope of this paper. It should be sufficient to say that the symbolic notational systems shown possess binary logic equivalent statements.

Normal drawing practices prevent the combining of electrical and mechanical inter-relationships on a large scale and make it necessary for test and checkout engineering personnel to assimilate this information through laborious, and error prone, search of large amounts of documentation. The "Sequence Diagram" system permits a description of the functional relationships of all system components to be described on one sheet of paper. (A three stage orbital launch vehicle is shown diagrammed in this manner in Fig. 7.)

The recent development of large Digital Differential Analysis programs has enabled us to envision supplementing the functional

sequence presentation with dynamic simulation of component status. Figure 8 shows a dynamic systems block diagram of a cryogenic component heater-thermostat assembly. Fig. 9 shows a computer generated output of an IBM 7094 run describing the dynamic performance of the heater thermostat system.

Lastly, we are presently attempting to combine the functional notational system, the digital dynamic simulation techniques presently available, and present ADPS techniques into a three language computer statement of the vehicle system configuration. This combination (Fig. 10) is presently referred to as the "Total Systems Definitive Statement." The feasibility of each language system has been proven and present efforts are being directed toward interfacing the three language systems with one machine system.

Besides providing engineering criteria with the TSDS system, a major hope of our project staff is to be able to apply this system to dynamic limits or dynamic comparisons testing of vehicle systems. A far future application of programs of this type will be found in on-line fault isolation based on heuristic programming techniques rather than anticipatory approaches to analysis.

FAR FUTURE VEHICLE AND CHECKOUT SYSTEMS

We have developed a number of concepts for future goals in various areas of automated checkout of space booster systems. If we assemble these various objectives into one listing we have a definition of what an "ideal" future space booster system may consist of:

1. The vehicle will contain comprehensive on-board stimulation capability.

2. It will be designed to contain components, sub-systems, and systems which will generate responses that contain information which will enable prediction of malfunctions.

3. It will carry response measuring equipment on-board the vehicle.

4. It will arrive at conclusions regarding its status by referring vehicle borne information about its own construction and operation.

If we succeed in reaching this ideal goal, we will still find man in the checkout loop. He will still be the agent that brings about repair of the system. We find that we must consider man's effectivness (Fig. 11) and methods of operation, mentally as well as physically (Fig. 12), when only five years ago our major requirements were only that he understand the system, be able to flip switches, and to read meters.

Let us now introduce the last characteristic of a far future vehicle system:

It will be capable of adapting, through alternate control path selection, through alternate operation modes selection, or other means, to failure of components and sub-systems. It will become an effective adaptable and autonomous device.

Thus, we will find future test and checkout systems will be integral parts of the vehicle systems and they will be configured in a manner comparable, in construction and operation, to the human nervous system. (Fig. 13)

SUMMARY

We have summarized the major problems attendant to comprehensive application of automatic checkout equipment to factory checkout of space booster systems. We have outlined some of our program efforts aimed at obtaining solutions to these problems. In conclusion, the major attributes of a far future vehicle system and checkout system have been listed as a goal toward which we should work. We have not attempted to establish a date upon which we will have such systems available.

Table 1. Distribution of In-Flight Malfunctions by Systems for Several Representative Large Liquid-Propelled Booster Vehicles.

SYSTEM	PER CENT
Propellant Pressurization, Feed, and Engine Systems	45
Control System (and all related subsystems)	38
Electrical System (networks and power control)	7
GSE, O Instrumentation and Destruct Systems	3
Structure	2
Miscellaneous	5

Table 2. Saturn Vehicle SA-5 Transferred Measurement Accuracy.

ACCURACY (end-to-end)	LOCATION	Number of Measurements
2%	Stage	1
	Instrument Unit	19
3%	Stage	19
	Instrument Unit	0
4%	Stage	1
	Instrument Unit	0
5%	Stage	110
	Instrument Unit	433

Table 3. Factory Checkout Transducer Rejections, Saturn I System.

MEASUREMENT TYPE	PRE-STATIC FIRING REJECTIONS, PER CENT	POST-STATIC & FLIGHT REJECTIONS, %
Pressure	7	11
Vibration	2	5
Temperature	2	3

Table 4. Saturn I Booster Factory Test Requirements; Comparison of Instrumentation System Accuracies and Transducer Location Requirements.

TEST	INDIVIDUAL OPERATIONS REQUIRED	MEASURING OPERATIONS REQUIRED*	ACCEPTABLE VEHICLE MEASUREMENTS
Electrical Networks	486	1559	12
Rough Combustion Cutoff & Fire Detection	653	310	0
Telemetry	26	13	0
Radio Frequency Systems	242	260	0
Guidance & Control Systems	798	483	0
Mechanical Systems	8592	5438	23

* Measurements required on-board the vehicle. This does not include ground based measurements of GSE and Test Equipment functions.

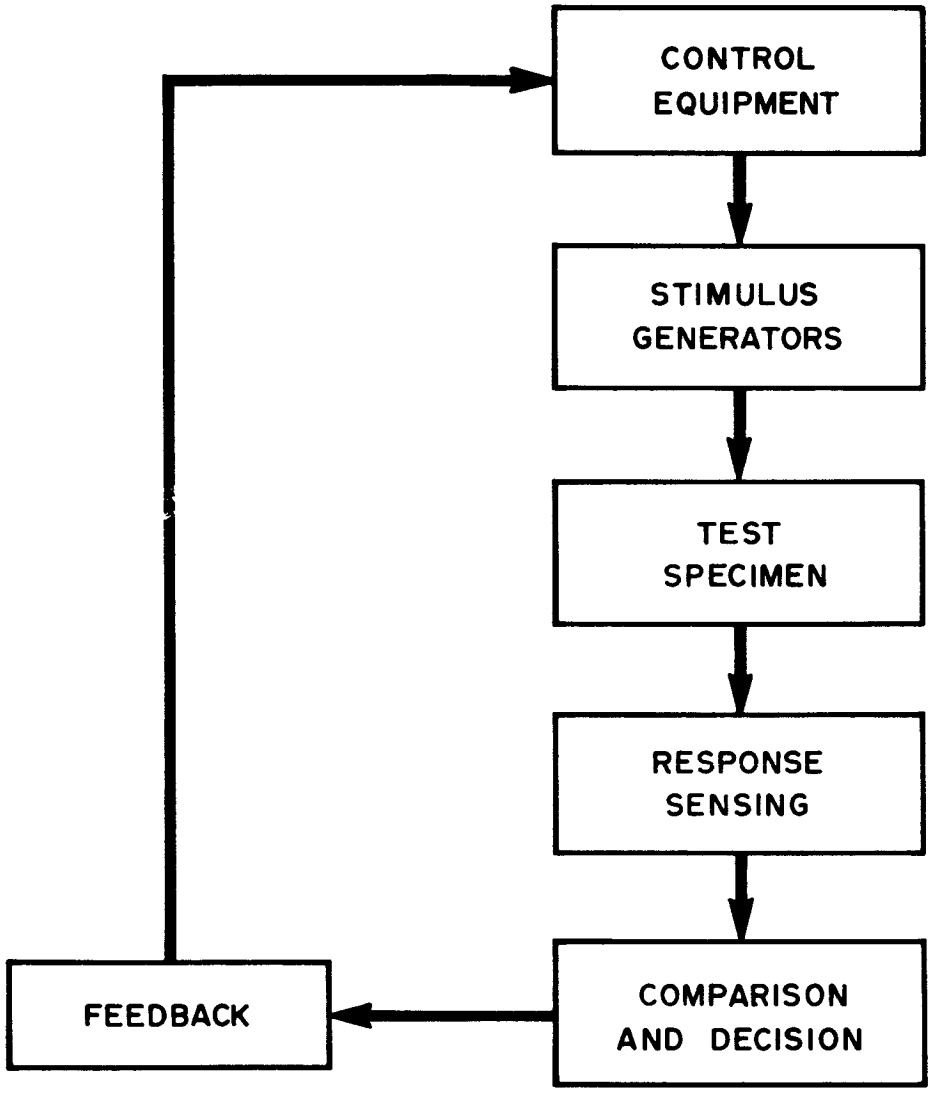

Figure 1. Idealized Factory Checkout

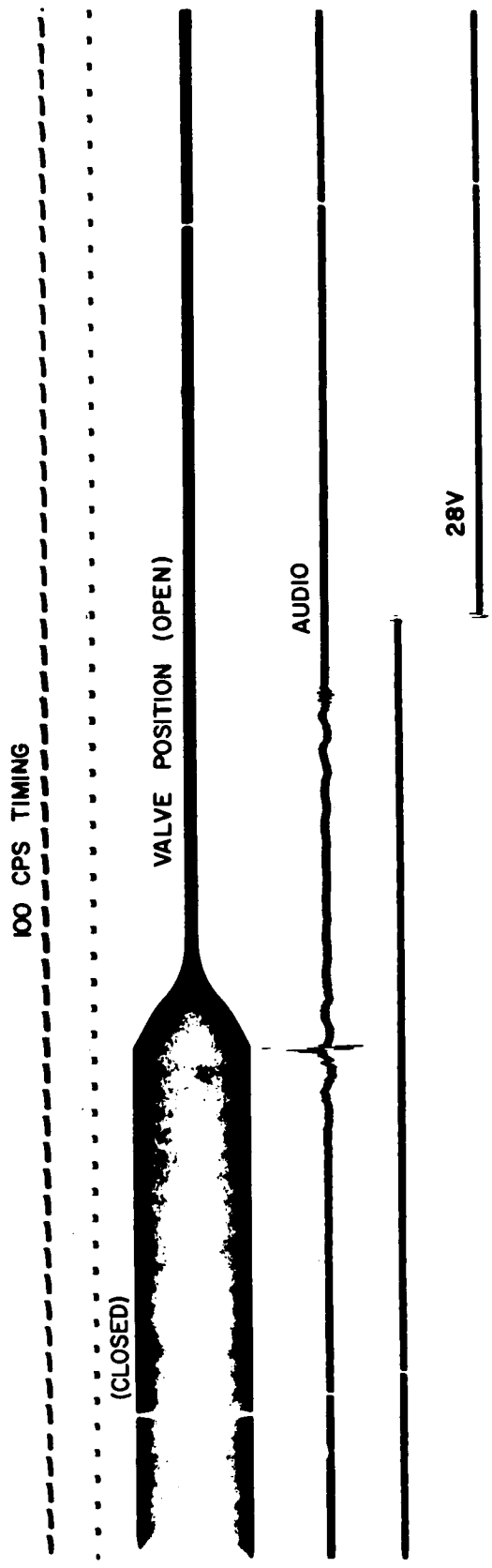

FIG. 2

MERCURY REDSTONE H_2O_2 VALVE TIMING OSCILLOGRAM

(BENCH TEST)

Figure 2. Redstone H_2O_2 Valve Timing Oscillogram

(Bench Test)

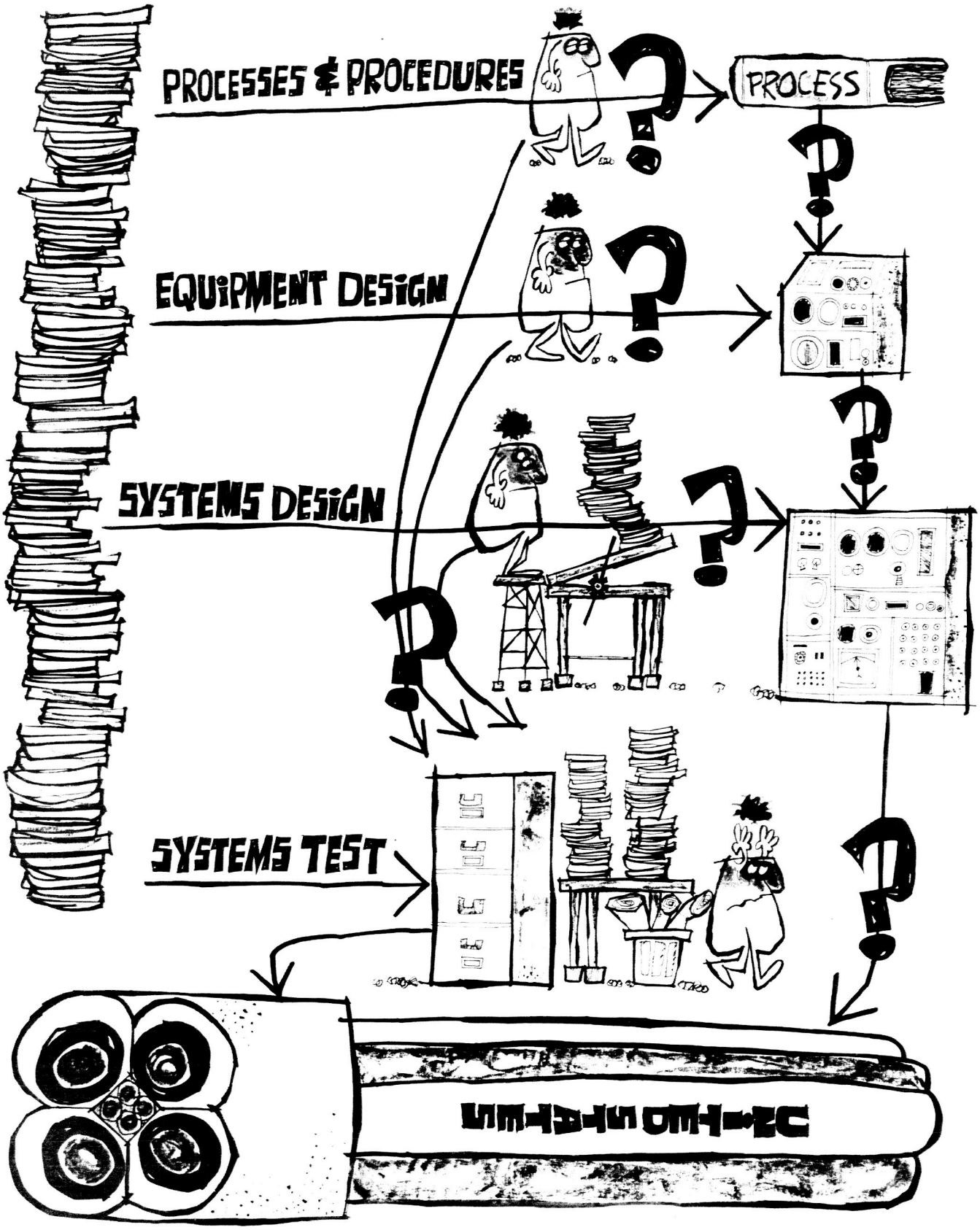

Figure 3. Some Error Sources in Checkout Operations

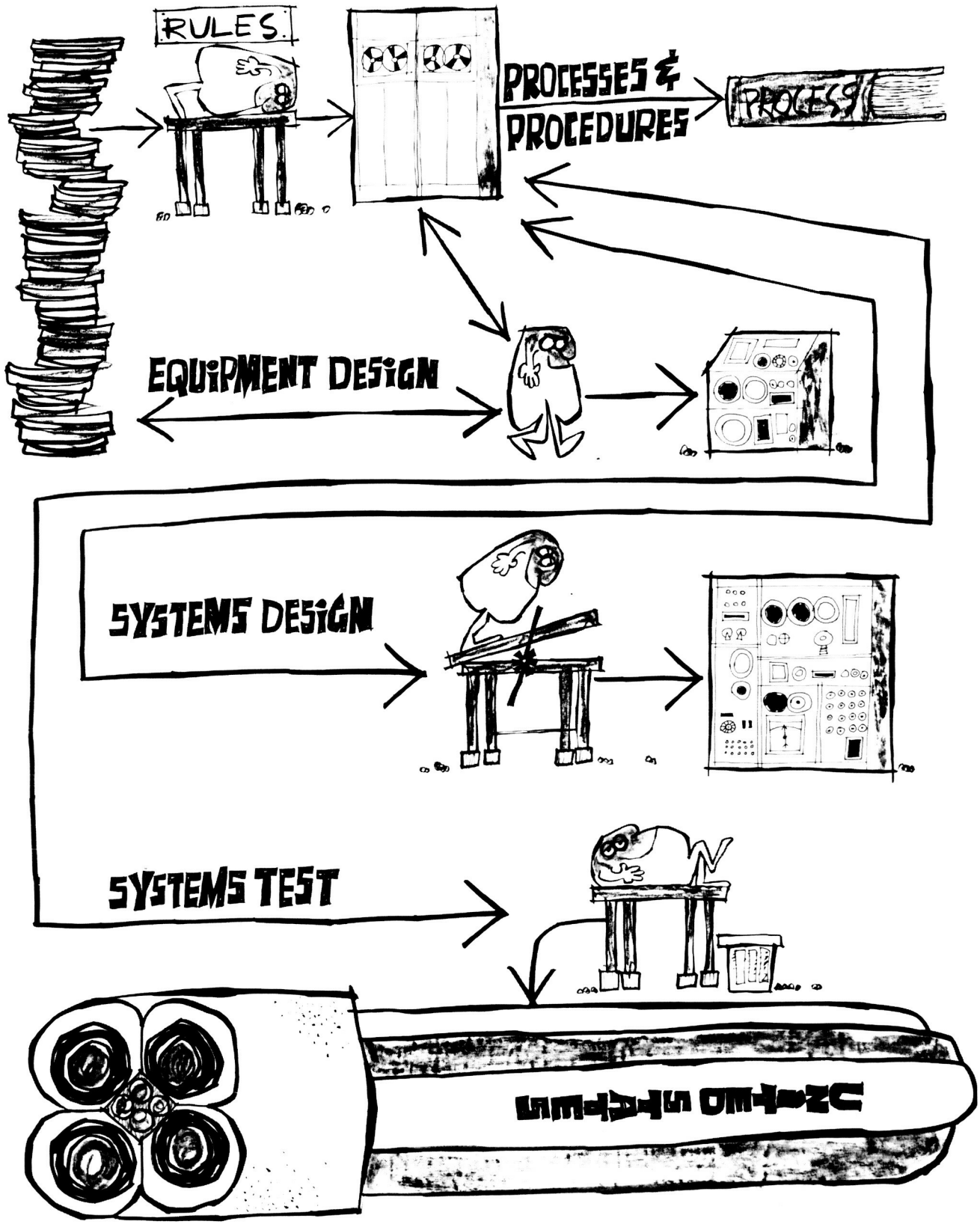

Figure 4. A Possible Computer Supplemented Checkout Operations Process

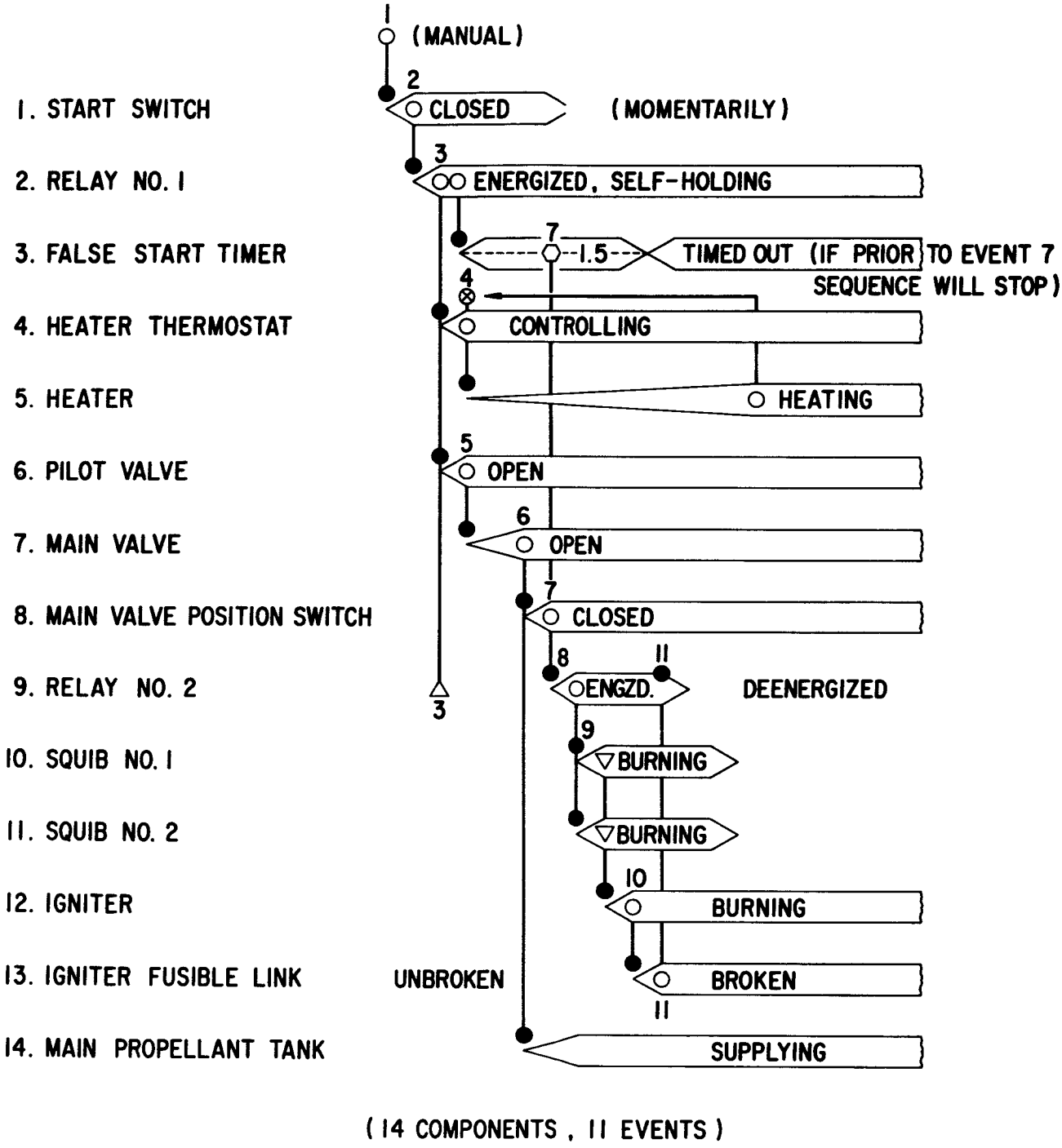

Figure 5. Illustrative System Sequence Diagram

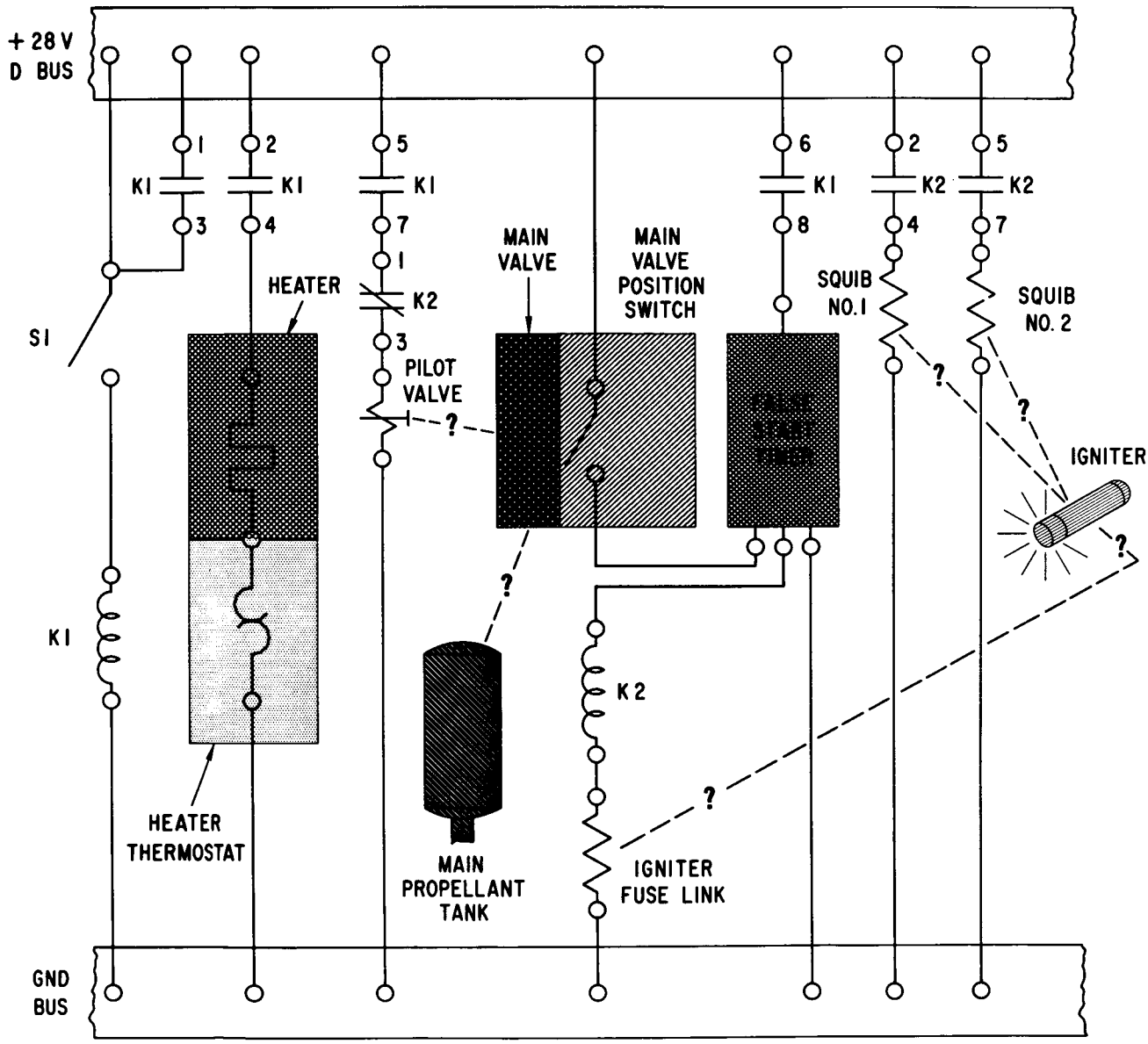

Figure 6. Illustrative System Schematic

Figure 7. Sequence Diagram For A Three Stage Orbital Launch Vehicle (Vanguard)

T_R - TEMPERATURE REFERENCE

T_O - PROCESS TEMPERATURE

M - B.T.U. INPUT TO PROCESS

N - THERMOSTAT HYSTERESIS

3. THE COMBINED SYSTEM.

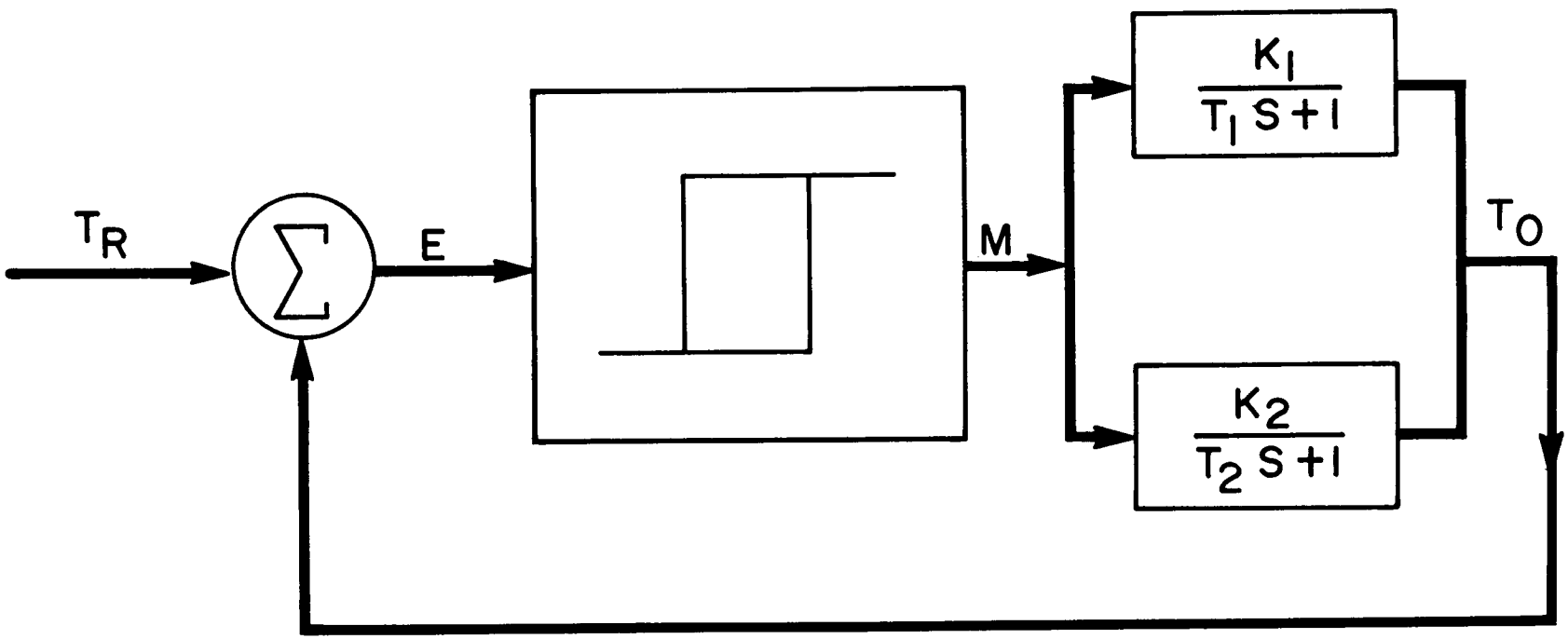

Figure 8. Heater System Dynamics Block Diagram

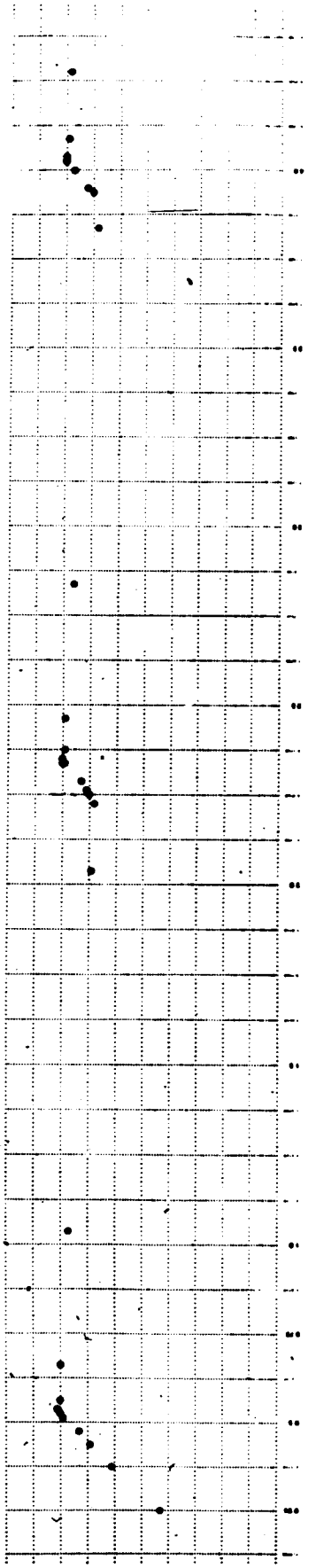

Figure 9. Computer Generated Printout Of Heater Responce
The Y-Scale and X-Scale Factors Are Both I.O.
The X-Origin Is O.

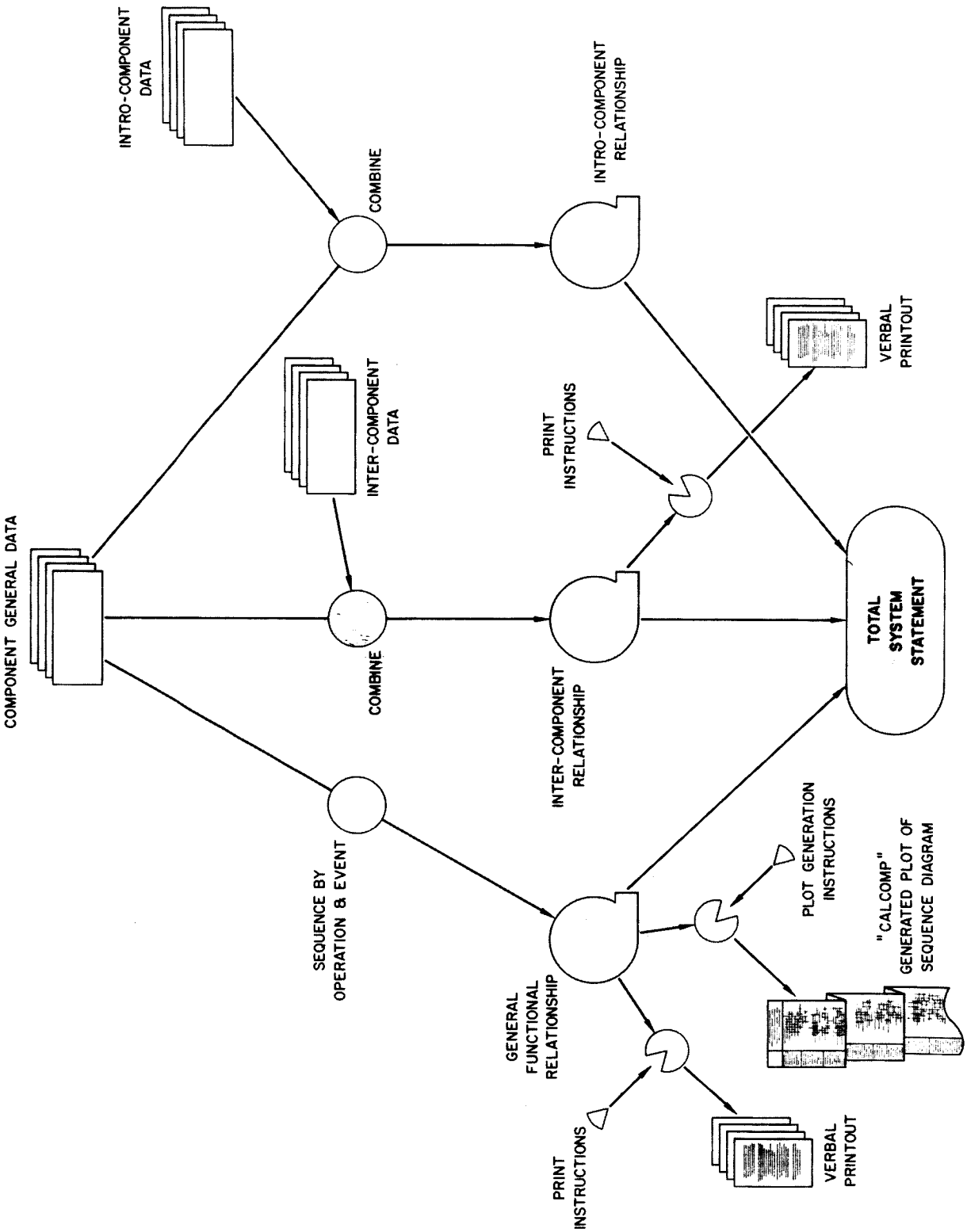

Figure 10. Total Systems Definitive Statement Generation Flow Chart Showing Example Outputs

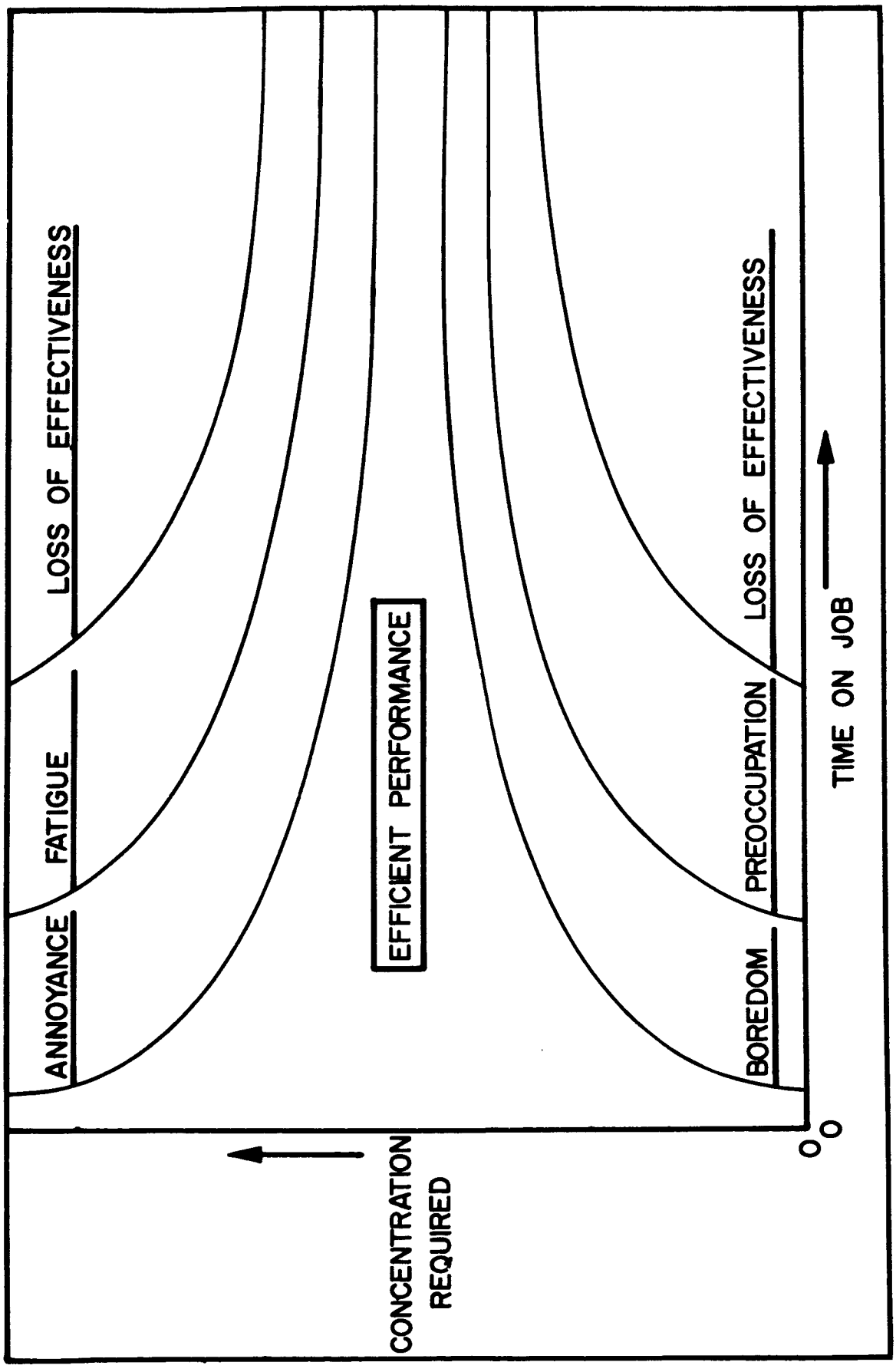

Figure 11. Human Effectiveness Characteristics Envelope

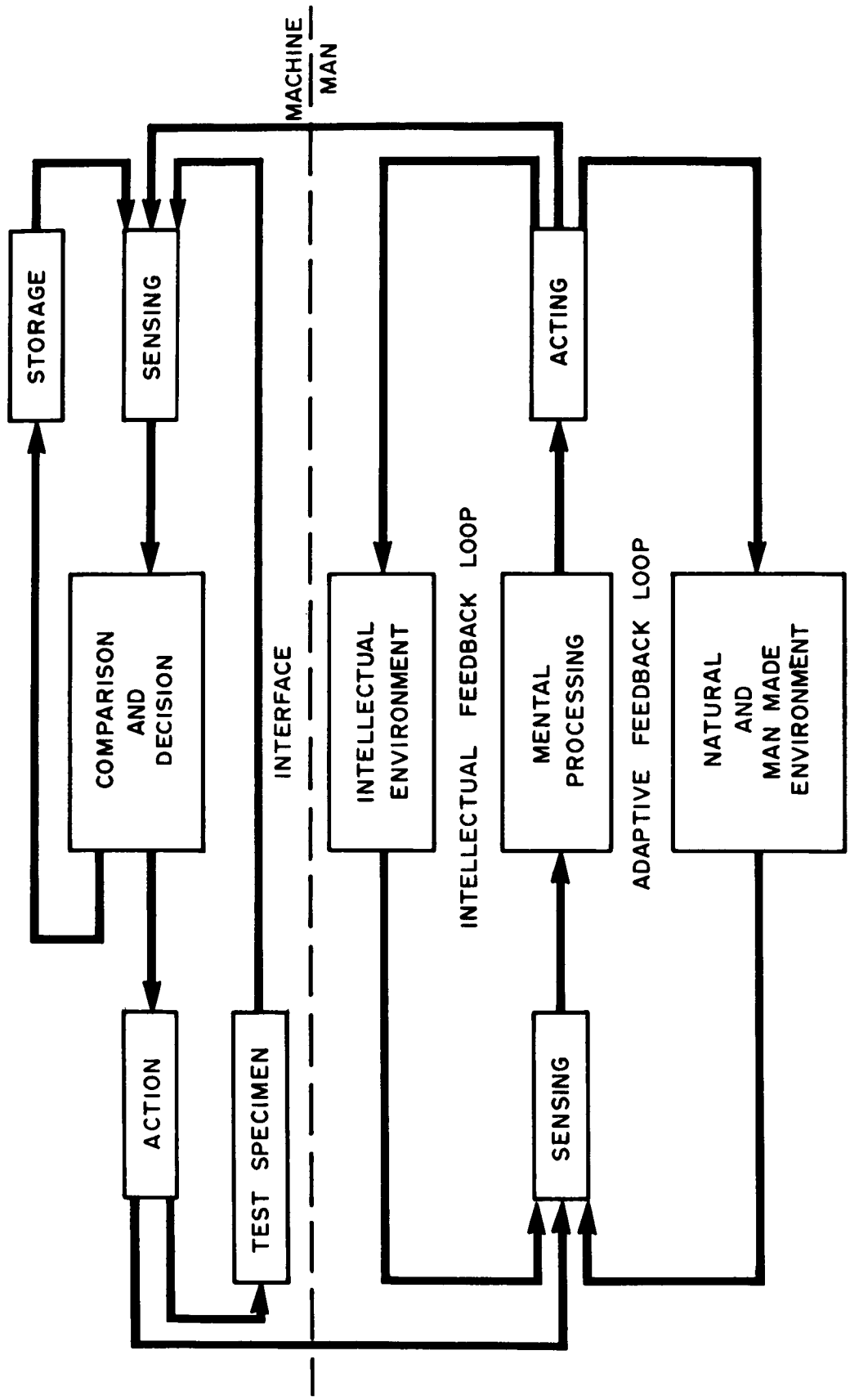

Figure 12. The Man-Machine Checkout System

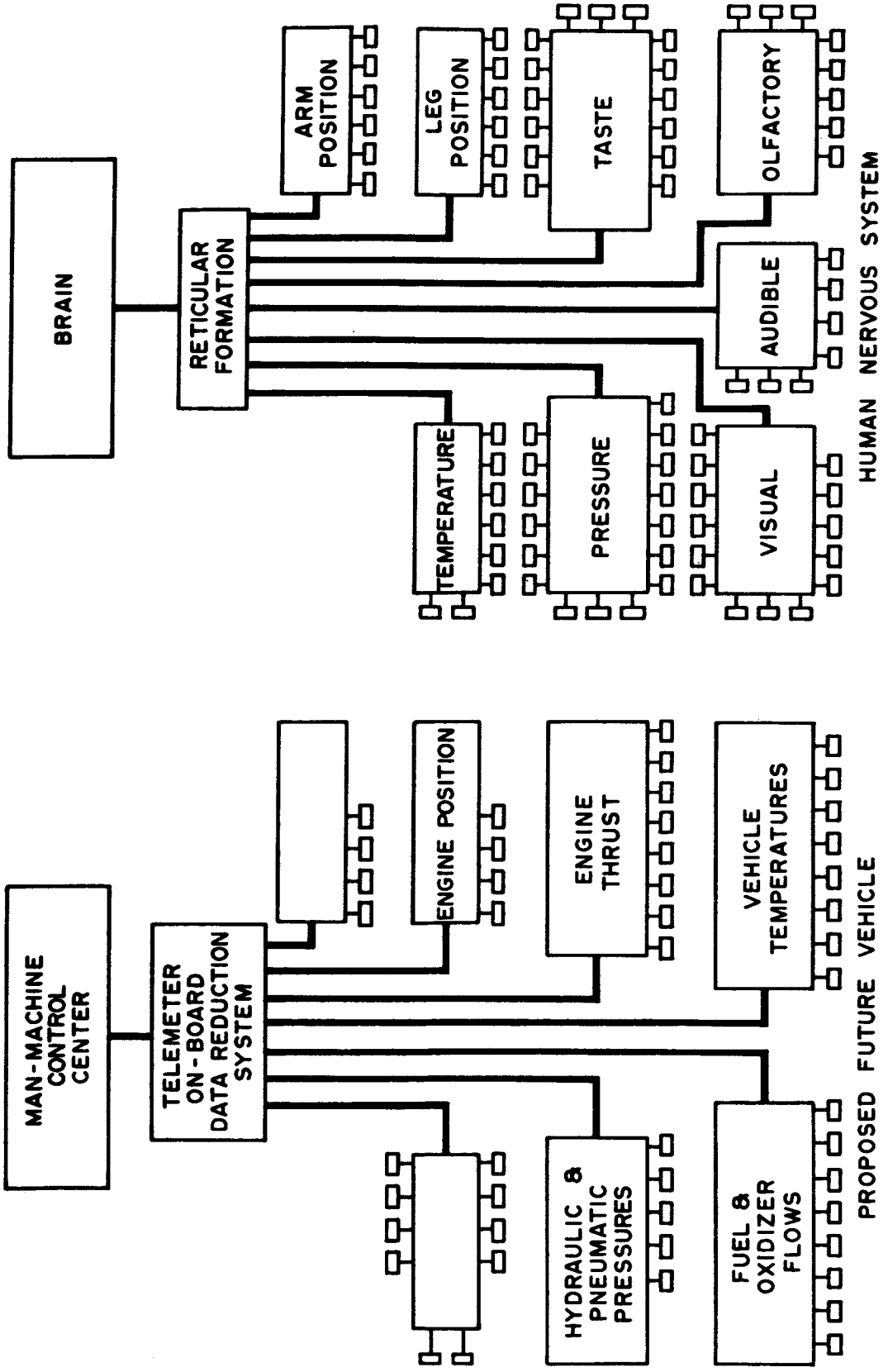
BRAIN
RETICULAR FORMATION
ARM POSITION
LEG POSITION
TASTE
OLFACTORY
AUDIBLE
VISUAL
PRESSURE
TEMPERATURE
HUMAN NERVOUS SYSTEM
MAN-MACHINE CONTROL CENTER
TELEMETER ON-BOARD DATA REDUCTION SYSTEM
ENGINE POSITION
ENGINE THRUST
VEHICLE TEMPERATURES
HYDRAULIC & PNEUMATIC PRESSURES
FUEL & OXIDIZER FLOWS
PROPOSED FUTURE VEHICLE

Figure 13.

COMPUTER-CONTROLLED AUTOMATIC TESTING

B. T. Joyce and E. M. Stockton

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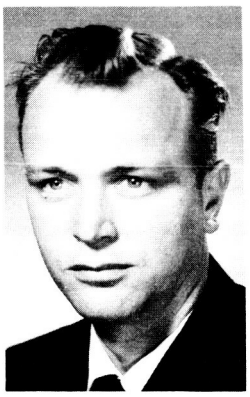
Mr. Joyce received his BS degree (University of Maine) and his MS degree (M.I.T.). He has been active in designing and developing aircraft fire- and explosion-detection equipment and specialized test equipment for infrared-sensitive devices; a variety of transistor circuits for airborne fire-control systems and checkout equipment. He had the responsibility for the electrical and mechanical design of the automatic programmed checkout equipment (APCHE) for the ATLAS missile; supervised the development of the RCA AM1100 digital differential analyzer and two general-purpose digital computers, the AM3100 and the AM3220; and was associated with the design and development of Multisystem Test Equipment (MTE) for the Army. Present position: Project Engineer for MTE test programming.



EUGENE M. STOCKTON, Radio Corporation of America (Burlington).

Mr. Stockton received his BSEE degree (Michigan State University) and his MSEE (Drexel Institute of Technology). At the RCA Defense Electronic Products, Airborne Systems Division, he was assigned to the design and development of the Air Force ASG 14 fire-control system where he worked on power supplies, receivers, transmitters, and synchronizers for radar devices; he has gained experience in every facet of Automatic Test Equipment with particular emphasis in system design, computer-controller design, and system integration and test. As design leader, he was responsible for the design of the computer used in the Multisystem Test Equipment developed for the Army Missile Command. Present position: Design Leader.

COMPUTER-CONTROLLED AUTOMATIC TESTING

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INTRODUCTION

Automatic test equipment has been going through a natural evolution. In particular, we have watched the changes in the basic digital control of the stimuli generation, the measurement facilities, and the test point selections. Control was first realized by manual patch boards, then by programmer-comparators of varying complexity, and more recently by general purpose computers.

The decision for using or not using a general purpose computer for control of automatic test equipment is dictated by a number of operational, environmental, and economic factors. However, computer-control is essential in maintenance type test equipment where diagnostic test programs must be prepared for many different kinds of units. Why? Simply, diagnosis in depth can only be accomplished in an indirect way through detailed examination of basic performance characteristics. Data must be collected and stored and then operated on by a series of calculations in order to obtain a measure of circuit performance. The same kind of test process followed by an engineer in laboratory testing, analysis and trouble-shooting must be translated to a test program. Such a program can be reasonably handled only with the power of computation, storage, and manipulation inherent in the general purpose computer.

With this type of need clearly established, we have included the general purpose digital computer in automatic test equipment, and we are materially rewarded in many other ways. Let us highlight some of the dividends:

(1) The computer comfortably handles a large test-programming load. Literally thousands of independent test programs will be prepared for use in diagnostic testing at the assembly or subassembly levels in different systems. The bulk storage problem becomes acute. Magnetic tape provides practical storage for this volume of test data and test control. The general purpose computer with its own internal memory and timing provides the natural vehicle for temporarily holding and processing those blocks of magnetic tape information associated with specific units-under-test.

(2) The program modification features of a computer reduce the length of a stored program having a given technical content. Basic sub-routines can be stored in memory, used over and over again, and modified to suit special test requirements.

(3) The computer gives considerable flexibility to the programmer in preparing a test design because he has at his disposal a number of tools for making logical manipulations and decisions. The computer has built-in instructions that permit transfers (branching) on various digital conditions--positive, negative, overflow, and zero. Other instructions allow manipulations of digital data through masking, complementing, shifting, and sign changing

(4) The general purpose computer can handle sophisticated mathematical analysis in isolating failures, assuring the future growth of diagnostic testing.

All of these statements favoring the use of a computer in automatic testing are quite general. Much of the material that follows departs from generalizations and shows specific cases of the powerful roles that the computer does play and will play in automatic testing.

THE "TYPICAL" TEST PROGRAM

Before we examine specific examples of computer utilization in diagnostic testing, let us review some summary data collected from an analysis of a number of actual computer-controlled test programs. These programs covered analog and digital devices, and combinations of both. They were prepared by personnel with varying skill, ability, and equipment familiarity. The programs were all associated with assemblies, such as chassis, containing replaceable subassemblies, such as module boards. It would be very helpful to be able to define a so-called "typical" test program; but you can be sure that what is typical today will not be so tomorrow. For one thing, test programming techniques are improving and equipment is becoming more readily tested as industry becomes more conscious of maintenance needs, such as the need for carefully selected test points. The unit-under-test itself varies widely in complexity. The following data at least may be useful in helping to indicate the general magnitude of the diagnostic type test program as we see it today.

The "typical" diagnostic test program consists of 100 tests with an average of 750 bits for each test. The total program uses about 75,000 bits of storage. Within this program there are some 3600 print characters (or 22,000 bits) used for messages. These messages identify the tests and the unit under test, give special instructions to the operator, and direct the necessary repairs. Significant reduction in the total amount of storage used for messages can be anticipated through more efficient use of the computer in handling repetitive commentary and by more careful planning of the message content and vocabulary.

The storage information was deliberately given in bits. These numbers can be juggled to reflect the number of computer words of different word lengths or the number of characters, according to the way you may like to express this information. To make the information more useful, we need to define the word "test". This, surprisingly enough, is somewhat difficult to do in simple terms. The very fact that a computer is used to control the test operations creates such a flexible situation that one test may include the analysis of many measurements to lead to several diagnostic conclusions. Let us try the following definition as being totally applicable to the word "test" as used here: "A test is that process of making one or more directly related measurements of a specific function to arrive at one or more diagnostic conclusions."

EXAMPLES OF COMPUTER UTILIZATION

Certainly many examples of computer utilization in diagnostic testing could be picked. Those examples that have been chosen are common to many test problems and punctuate the importance of computer-control.

Digital Equipment Evaluations

The advantage of a computer-controlled test set is vividly revealed when testing a digital type unit-under-test (UUT). A multi-bit digital word can be inserted into the computer memory from the UUT with a single interrogation. Once the UUT message is in the memory, the full computer flexibility is utilized. As with the programmer-comparator a direct comparison with the desired results can be made. The advantage of the computer comes into play if the UUT does not behave properly. With a comparator only a greater or less-than result can be accomplished. With a computer, depending on the type of digital function being observed, there are alternatives that can be programmed.

If a straight transfer-type digital function is being examined, a shifting routine can find all false channels and print out the total failure upon examination of all channels. Knowing what message should have been fetched into the computer, the progam can successively shift the data, one bit at a time in the accumulator. Each bit, as it is transferred into the sign position, is examined by the logic decision instructions, transfer on positive, or transfer on negative depending on the desired results. Each time a malfunction is detected the shift number can be stored in a predestined position in memory. In this manner, the whole word is examined and the results can be printed out with one message listing all malfunctioning channels.

Another method that may be programmed is taking a numerical difference. This method is used to best advantage on a digital assembly that does some manipulation, and not a straight data transfer. Again, the programmer knows what result should be derived from the specific problem fed to the UUT. The actual test result is subtracted from the desired result, and a numerical difference is determined. Utilizing the transfer on zero logic decision a correct result can be ascertained. If the result is not zero, its absolute magnitude can be established. Knowing the operation of the UUT the test designer can predict a large portion of the faults in this manner. Specifically assume that the tested device is an arithmetic unit from another computer. A series of addition problems could be inserted and the results, or difference of results, from correct responses would be stored in memory. The results could then be analyzed

to determine the cause of incorrect bits. A feature mentioned before which comes into action when testing digital units is the ability of the program to modify itself. The series of addition problems to be inserted into the arithmetic unit mentioned above could well depend on the results of the previous comparison in the series.

Depending on the sophistication of the computer in the test set, the implementation of a masking function could greatly aid digital-type tests. By performing a masking function between the desired results and the actual results, the actual bits that are different from the expected results are what remain. The masked result could then be operated on with the methods mentioned. By shifting and examining the masked results and storing the shift count, the exact channel discrepancies are isolated.

By taking advantage of a high speed computer as the source for digital messages to a unit-under-test, more accurate real time testing can be performed. The computer does not have to compare each message as it is generated, but instead store each response in the memory at a speed limited only by the memory cycle time. Thus a series of digital stimuli could be sent to the test device, with a series of results coming back for immediate storage. These results could be analyzed after completion of the high speed data collection.

Analog Circuit Evaluation

It is very apparent that the general purpose computer has considerable flexibility for manipulating multi-bit responses from digital type devices to localize failure modes indicated by the various bit combinations. In such operations, the logic-, shift-, and transfer-type instruction dominate the diagnostic program, although some add and subtract instructions also appear. The computational, or arithmetic, capability of the computer really comes into play in the examination of analog circuits where detailed fault diagnosis requires calculations on response data. Many important circuit performance-characteristics that provide clues to finding troubles can be obtained only indirectly. Let us examine two typical examples that illustrate this important use of the computer: (1) a test of power supply load regulation and (2) an amplifier bandwidth measurement. These examples are particularly appropriate in that they are likely to be found in many major subsystems requiring fault isolation.

Power Supply Load Regulation

A regulated power supply normally has an allowable range for its nominal output voltage that may or may not be adjustable. Even when adjustable, the absolute voltage setting is not critical. But, very critical to the performance of the supply is the specified regulation it must provide against load current change. Load regulation is a direct measure of output resistance, a characteristic very important to the circuits that load the power supply. If this resistance is excessively high, even though the voltage is still within its specified limits, amplifier circuits can become oscillatory, flip-flops can trigger falsely on noise, and for that matter, the performance of a whole system can be degraded by the undesired noise on the power supply lines.

How is output resistance measured in the computer-controlled test system ? First the computer directs the measurement of the power supply voltage under one condition of load (perhaps no load) and records the answer in digital form in memory. Then it makes another measurement of the voltage under a different condition of load (perhaps full load). The computer calculates the difference between these two voltages and divides this difference by the change in load current. Thus it has a measure of the power supply output resistance. The value of output resistance can then be evaluated against the programmed limits determined from the performance specification. It should be noted here that an element of sophistication in these measurements is possibly desirable. The nominal power supply voltage setting may lie between rather wide acceptable limits and the loading may be accomplished with resistors rather than with constant current loads. For these reasons, intermediate calculations may be required to determine more exactly the currents involved in the two load measurements and in order to find accurately the current difference.

Amplifier Bandwidth

There is a broad spectrum of linear amplifier performance-characteristics associated fundamentally with measurements of gain and bandwidth. In

the example to be illustrated we have the case of a relatively narrow band amplifier where the nominal gain is quite variable and we have the problem of finding out what the bandwidth is. The computer goes through an incrementing process to generate a series of signals at different frequencies and stores the resulting responses in memory. It then examines this accumulated data in a sequence of comparisons to find the maximum response. The computer can at this point make a check of the signal amplitude against predetermined programmed upper and lower limits or calculate the gain by dividing the output signal by the measured input signal and make the comparison against the normalized limits of gain. Now that the maximum point of the response curve of the amplifier is known, the computer is used to calculate the signal amplitude at the half-power points (0.707 times the maximum signal) and determines the signal frequency at these points. Here it is practicable for the computer to interpolate in order to find the frequencies more exactly. The difference between the upper frequency f_2 and the lower frequency f_1 is computed to obtain an accurate measure of bandwidth - a performance characteristic that could not have been obtained without computer-controlled test equipment.

Minimization of Program Storage Required for Print Out Messages

In a programmer-comparator a large portion of the file storage is used for storing print-out characters. Due to the serial sequencing of the paper tape each message must be programmed in total. A careful study of the types of print-outs show that messages fall into several patterns. One typical message pattern consists of instructions to the repairman to replace a faulty part or subassembly; another typical message consists of instructions to the operator to make some adjustment on the unit under test. By utilizing the addressable memory and program modification capabilities of the computer, common messages can be stored in specific memory locations. During the test, the results of previous measurements and analysis will dictate which of the names or identifications will get inserted into the canned message. In this manner, the basic prose for each pattern of messages has only to be stored once. This utilization of the computer flexibility not only reduces the amount of program storage required but also dictates a common format for messages to be printed out, so that there is less likelihood of confusion in the message content.

SIMPLIFICATION OF AUTOMATIC TEST EQUIPMENT THROUGH COMPUTER CONTROL

We have come to appreciate that computer-control leads to simpler and more flexible test programs and permits more penetrating and revealing tests. We are really working in a relatively new engineering specialty field; automatic test engineering could be its name. The test engineer is being married with the computer engineer. By training and by instincts these people have been separated. Neither fully appreciates the technology of the other. They differ from each other like analog differs from digital, like "maybe" differs from "yes or no". As we watch automatic test equipment evolve, we will see the rewards of a happy union of the two engineering disciplines. When a general purpose digital computer is part of an automatic test system, it makes sense to take a hard look at the variety of special test equipment contemplated for inclusion to see what can be eliminated or simplified by taking advantage of computer directed "intelligence".

In the modern engineering laboratory we find all kinds of test equipment to suit every peculiar technical need. It is well to reflect that many of the measurements made today with sophisticated, complex equipment were made and still can be made with relatively crude devices by classical testing techniques. Take an amplifier gain measurement, for example. The amplifier can be driven from a signal generator designed to deliver accurate signals scaled to the appropriate required input level; and then the output signal can be measured absolutely with another accurate piece of test equipment. Gain is calculated by dividing output by input. This same measurement can be made with cruder equipment and yet be made more accurately. It is really not important that the signal generator be accurate but rather that it have good short term stability. Let a crude signal generator drive a precision attenuator which in turn feeds the amplifier. The attenuation is selected to yield an output voltage from the amplifier that closely approximates the input voltage to the attenuator. A piece of test equipment is used which makes a relatively crude measurement of the signal difference. A calculation involving the output signal, the difference signal, and the attenuator setting leads to a highly accurate measurement of gain. A review of basic test techniques and incorporation of these techniques into real hardware and test programs in computer-controller test equipment will bring to the user hardware simplifications, better test results, and improved system reliability.

Let us look at another example where computer-controlled test equipment can be simplified. Servo mechanisms often require very low frequency signals for stimuli either directly or for modulating higher carrier frequencies. With computer-control it becomes practical to eliminate any need for having as part of the test equipment complement an identifiable signal generator for these frequencies. The digital-to-analog converter (DACON) for delivering DC signals is a fundamental element of any comprehensive automatic test system. The computer can be programmed to change the digital words that control the DACON continually in a quantized fashion to synthesize a sine wave of the desired frequency and amplitude. There are several forms that the program may take to do the job of controlling the DACON. One method can be examined superficially to illustrate the principles involved. First, a normalized set of digital words would be stored in memory. It would take four-hundred 8-bit data words to generate one cycle of a sinusoid generated from a DACON controlled by the states of two BCD characters. If the normalized set of words were sent out sequentially to the DACON, the peak value of the sine wave generated would be equal to the maximum voltage that could be delivered. For any other voltage lower than the maximum, the computer would modify this list by multiplying each value by the appropriate factor. The speed for outputing the data words would be established by a simple subroutine using index registers. It is quite reasonable with a good medium speed computer to control the DACON output to provide a 1% sine wave stimulus up to 100 cycles per second.

In a similar fashion, the computer can, by control of the DACON, generate low frequency saw-tooth, square wave, or triangular waveforms. For that matter, it can be used to produce any complex repetive pattern or profile within the limitations of its processing speed.

SUMMARY

The digital computer assumes a very active and powerful role in controlling automatic test equipment. It is a vital component of the test system because it can, through its ability to calculate, through its capacity to remember, and through its faculty to make decisions, isolate faults to a level normally attainable only by the skilled engineer. The computer provides the test designer with a flexibility that eases the programming problem and permits a reduction in the size of the total program. It readily accommodates mathematical diagnostic techniques as they are perfected and opens the door to simplifications in the stimuli and measurement equipment that it controls.

A COMPUTER-CONTROLLED INTEGRATED CHECKOUT SYSTEM

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A COMPUTER-CONTROLLED INTEGRATED CHECKOUT SYSTEM

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INTRODUCTION

The evolution of checkout equipment for avionic systems has progressed from manual to completely automatic.

In the past, the development of checkout equipment has traditionally lagged behind the development of avionic systems. Among the reasons are that emphasis was placed primarily on performance, and checkout equipment was usually designed after the avionic system had been developed. Furthermore, the checkout equipment was designed by a new team, not the prime system designers.

The manual tester frequently has been nothing more than a multimeter with a convenient arrangement of test points and test point switching. It required a highly skilled operator, thoroughly familiar with the system being tested. The checkout time and the time required to localize a fault were quite unpredictable, since they were so strongly dependent on the skill of the operator.

As the complexity of avionic systems increased, the shortage of skilled maintenance technicians became more acute; more effective checkout equipments had to be developed. In many cases, the swing to automatic checkout equipment was too zealous. Large, completely automatic ship-side testers surpassed in complexity the equipment they were testing. Although no great skills were required to operate the test equipment (when it was working), many new problems arose. Maintaining the test

equipment required new skills. The complexity of the testers made them unreliable and this tended to destroy operator confidence. As a result, many of these testers fell into disuse.

From the lessons learned in this painful growing-up process, a new generation of testers, combining the advantages of automatic testing and the decision-making capability of an operator, was developed. A successful example of this type of tester is the UG-1000 flight line analyzer for the F-104 AFCS.

EMPHASIS ON SYSTEM EFFECTIVENESS

For a system to completely fulfill its mission, it must not only meet performance requirements but must perform its mission with a specified confidence at an acceptable cost. Experience shows that the initial system cost is not nearly as significant as are the subsequent costs required to maintain the system in a state of readiness.

To achieve optimum system effectiveness it is imperative that the maintenance concept be developed concurrently with the system; in this way the responsibility is undivided. Many tradeoffs between performance, reliability and maintainability are possible; they should be made in the early design stages when considerable freedom exists.

THE MAINTENANCE CONCEPT

The system considered here is for an aircraft and maximum availability and probability of mission success are highly desirable. No inflight repairs are possible.

Mission-success probability is enhanced by, first, designing reliability into the system and, second, performing a thorough checkout as close to the initiation of the mission as possible.

To optimize availability, the checkout interval, including setup and the mean time to make a repair (MTTR) should be short, and the mean time between repairs (MTBF) should be long. The MTBF requirements will in most cases be determined by the mission success probability. The MTTR is a function of the time required to isolate the fault to a line-repairable or replaceable assembly after the system had been shown to be inoperative, and of the time in which the actual physical module replacement or repair can be effected.

Both these parameters can be subject to control during the system design process. The repair or module replacement time depends on the packaging concept, and the fault-isolation time depends on the efficiency of the check-out equipment.

A ship-side tester can be designed to be fast and efficient; but, there are several disadvantages associated with this type of tester that are unlikely to be overcome in the near future.

One is the necessity of sharing one tester among a number of aircraft. This precludes the possibility of a checkout immediately preceding each mission. Simple economics forbid the wasteful use of a separate tester for each aircraft.

Another is the fact that the tester must be transported to the side of the aircraft (or vice versa), a time-consuming activity which has definite practical limitations.

Also a disadvantage is that this type of tester normally has a large number of cables which must be attached to the system under test. The power requirements of the tester usually are of a magnitude to require a source outside the aircraft.

Experience shows that the time required to prepare for a checkout can be many times as long as the actual checkout interval. These problems can effectively be eliminated by making the checkout system airborne and integrating it with the avionics systems.

The maintenance concept adopted for the purpose of this discussion includes these elements:

- A quick premission test is performed, giving a GO-NO GO indication without use of equipment external to the aircraft
- The airborne checkout equipment isolates faults to a line-replaceable assembly, such as the inertial reference package or a major portion of the automatic flight control system
- Repairs on the flight line are limited to substitutions with spare assemblies
- All repairs on the assemblies are performed in the shop or at the depot

THE CHECKOUT SYSTEM

Justifying an airborne computer solely for checkout would be difficult indeed -- from the standpoint of both economics and weight. Besides a computer engineer would rebel at the thought of his computer being used intensively for short intervals separated by large spans of idleness.

There are, however, aircraft which have a digital computer as part of their avionic systems. By time-sharing this computer, an economical solution for the airborne checkout problem is possible and feasible. If the checkout problem is considered in the initial design stages, it is

possible to specify the required additional computer capability which would permit its use for the checkout function. Usually, this additional capability involves only sufficient memory to accommodate the test programs and, possibly, a separate data input and output channel.

Such a checkout system is block diagrammed in Figure 1. It consists of a digital computer and a digital clock, both part of the existing avionic systems, and these added components, solely for the checkout function:

- A display and control panel
- An input register and instruction decoding logic
- Stimulus generators and associated switches
- Test point selection switches
- Signal conditioners
- An analog-to-digital converter, which also performs as a digital counter.

A closer look at these component blocks follows:

The Computer

The computer characterisitics are dictated by the avionic systems for which it is primarily intended. The checkout system does not impose any special operational features on the computer, but rather, utilizes its general purpose characteristics. The notion that "the computer can do everything" has been discarded. For example, the computer is not used as a function generator through an analog-to-digital converter, nor is it slaved to the tester through interrupts. The test program is interleaved with, and executed concurrently, the normal computer programs

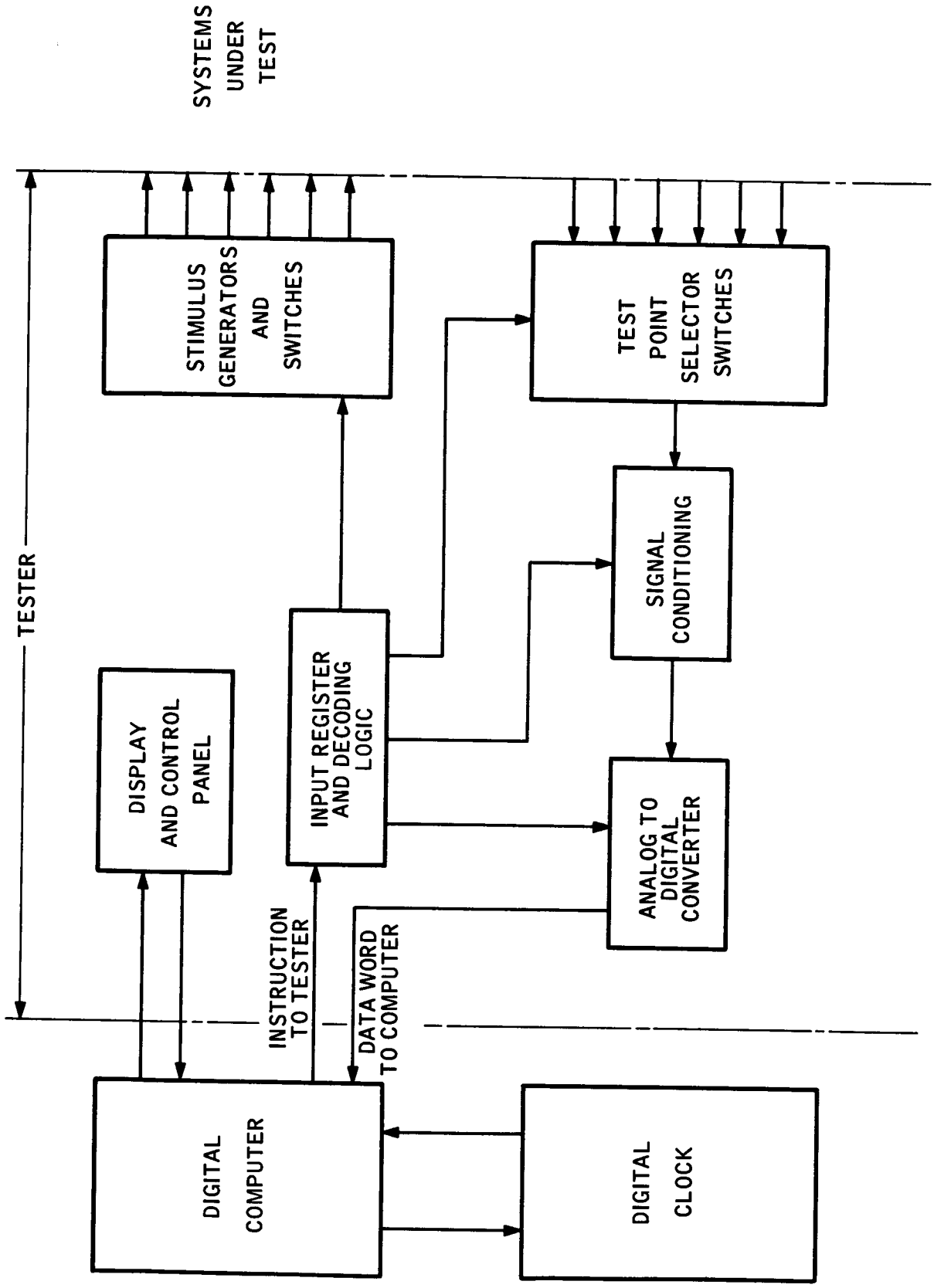

Figure 1. Checkout System Block Diagram

The functions of the computer in the tester are:

- Sequencing of tests by serially transmitting instruction words to the input register of the tester
- Making time-determinations by referring to the digital clock
- Evaluating measurements received from the analog-to-digital converter

The last function is the most important. It is here that the computer's versatility produces dramatic advantages over testers employing simple comparators. The computer, in many cases, is called on to make decisions based on several measurements related by a known mathematical function. This is significant because complete freedom of stimulus application is sometimes denied in the testing process.

The Digital Clock

Associated with the computer is a digital clock. It is used in making time-constant and frequency determination. The useful resolution of the clock is in the order of a millisecond. It is limited by the frequency with which the computer has access to the clock.

The Input Register

The input register accepts serial instruction words from the computer, decodes them, and routes them to the proper component block. Each instruction controls only one function. For example: apply or remove a stimulus, select a test point or command the A/D converter to hold the last reading and send it to the computer. The input register also includes a parity checker to guard against data transmission errors.

Stimulus Generators

Stimulus generators provide signals for injection into the system under test to excite it into producing an expected response. A great variety of stimuli exists, but most are simple circuits which generate d-c voltage or various frequencies, or apply known loads to the system under test. Stimulus-application is controlled by solid-state analog switches. The generators and the switches are integrated with their respective systems. This is advocated because (1) it eliminates long leads at sensitive circuit points, (2) each stimulus generator is peculiar, and (3) expansion or changes in an avionic system will impose no modification requirements on the tester proper. Each stimulus generator switch incorporates its own memory, so any number of stimuli may be applied simultaneously.

Test Point Selection

Test points are selected only one at a time and are presented to the A/D converter through precision solid-state analog switches. These switches also are integrated with the system under test. Test points are judiciously selected, so signals require a minimum of conditioning. Where necessary, individual test point signal conditioners are provided to bring signals to the desired amplitude or impedance level before switching.

Each switch should be sufficiently isolated from the test point that switch failures will have no appreciably degrading effect on the system. This is, in most cases, easily accomplished through the use of series resistors. The problem of fail-safety is much more difficult with the stimulus generators.

Signal Conditioning

As mentioned, most of the signal conditioning is done directly at the test points on an individual basis. However, in a few cases where the signal conditioner complexity increases, it may be more practical to share one signal conditioner among a number of test points. Examples of these are ac-to-dc converters and zero-crossing detectors for frequency measurement. The input to these shared conditioners are at a high level, in the order of several volts. All millivolt signals are preconditioned to this level before switching.

The Analog-to-Digital Converter

The analog-to-digital converter is the most important component of the tester. The A/D requirements in this application are different from those for sampled-data systems. Here, the switching from test point to test point is at a relatively slow rate; it is limited by the fraction of computer time available for the test function. There exists, however, a requirement for tracking waveforms changing at the rate of several hundred volts per second. A successive approximation type of A/D converter would be required to make more than 10,000 complete conversions per second to follow such a waveform. This is a very fast converter, and its per-bit apperture is so narrow as to make it vulnerable to microsecond noise spikes. An A/D converter has been developed at Honeywell which is ideal for this application. It is a tracking instrument, capable of following a 200-volt-per-second change at its input. If a step change exceeding 10 bits occurs at its input, the converter changes to a mode which is comparable in speed to that of a successive approximation converter capable of 1000 conversions per second. As the converter catches up with the input, it reverts to the tracking mode. The advantages this converter offers are:

- High apparent conversion speed
- An order-of-magnitude greater noise immunity than equivalent successive-approximation converters
- Slower and, therefore, simpler and more reliable analog components are required for its mechanization
- The converter tracks the input until commanded to freeze, then holds the last digital value for assimilation at the computer's leisure. This feature is utilized in conjunction with the digital clock in making frequency-response and time-constant measurements.
- Since the converter register is basically an up and down counter, it is easily adaptable to frequency measurement. The test point signal is applied to a zero-crossing detector whose output then serves as the clock for the converter register. The computer generates the counter gate by using the digital clock and the converter-freeze command.

ADVANTAGES OF AN INTEGRATED CHECKOUT SYSTEM

Some of the advantages offered by an integrated, airborne checkout system, such as increased availability and increased mission success probability, have been indicated. Some other advantages are:

- The system designer is forced to consider maintainability. The system-tester interface is resolved -- at the time it can most easily be accomplished -- during the initial system design.
- Sensitive test points need not be tied to long cables, making the measurement job simpler and reducing the possibility of the introduction of external noise to cause erroneous readings.

- The logistics problems are greatly simplified, resulting in faster turn-around time. The technician skill-level requirements at the flight line are greatly reduced. Repairs on major line-replaceable assemblies are accomplished in the shop, where more elaborate testers and technicians with higher skills can be utilized more efficiently.

DISADVANTAGES AND PROBLEMS

As is often the case, the advantages come at a cost we may not always be willing to pay:

- The checkout system means additional weight carried by the aircraft. This weight is for equipment that makes no contribution to performance; but, by using integrated circuitry, this objection may be minimized.

- Since the tester is integrated with the system under test, increasing total system complexity, tester failures can greatly degrade system reliability unless carefully guarded against. The component-count of the tester is comparable, for example, to that of a navigation computer.

- The tester is a digital system, employing memory flip-flops. These are susceptible to noise and transients which may have a very low frequency of occurrence.

Measures which will minimize the effect of tester failures on the avionic system performance include self testing, parity checking, stimulus and test point isolation and disabling the tester on completion of checkout. The latter cannot be accomplished completely, since the stimulus and test point switches still remain a physical part of the avionic system. However, the remainder of the tester can be effectively isolated. Disabling the tester

is justifiable, since testing after the initiation of the mission can not improve the mission success probability if inflight repairs are not allowable.

DETERMINATION OF TESTER REQUIREMENTS

The buyer of an aircraft wants two things for his money -- a specified level of performance and a specified availability for this performance. The buyer also expects a certain utilization from the system, based on the duration of each mission and mission frequency.

Availability, mission duration and mission frequency determine the system utilization profile (Figure 2). From this utilization profile are derived the system reliability and the tester requirements which will ensure achievement of the availability goal.

Availability can be defined as

$$A \equiv \frac{MTBF}{MTBF + MTTR}, \qquad (1)$$

where

A = availability

MTTR = mean time to repair including fault detection and isolation time

MTBF = average value of the mean time between failures during available time; it is composed of two components -- an operating MTBF (on) and a nonoperationg MTBF (off)

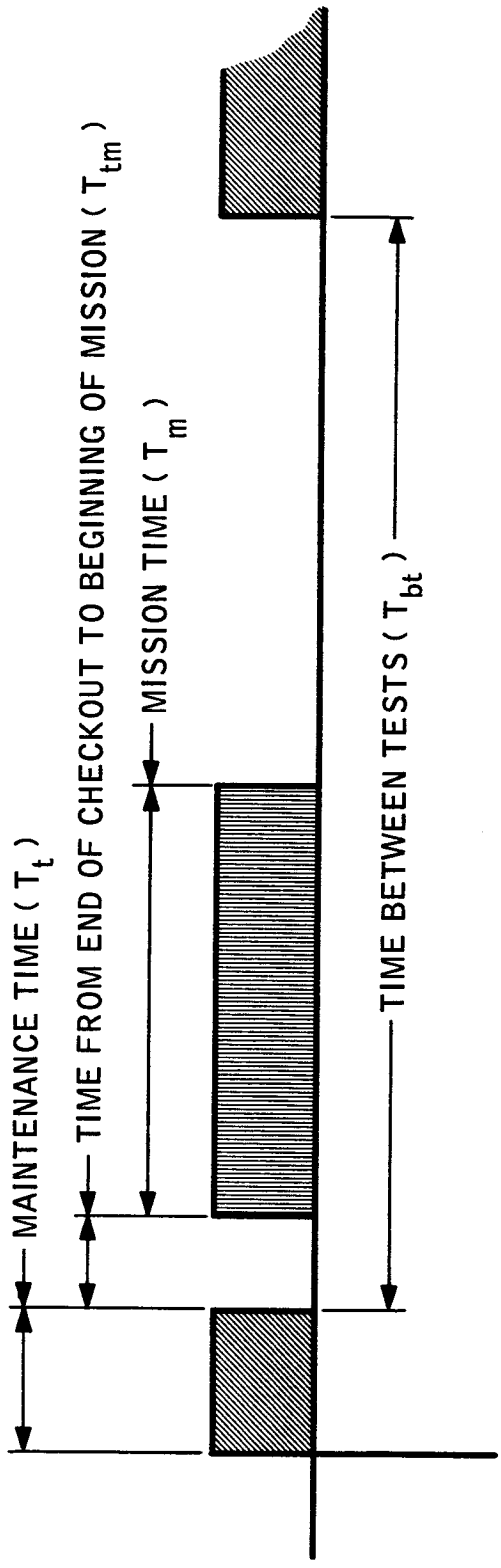

Figure 2. System Utilization Profile

Tester performance is specified by defining the following:

α ≡ the probability that the tester will call a good system bad

E ≡ efficiency of the tester, fraction of good systems called good

If it is required that N fraction of the systems pass the checkout,

$$\alpha + (\lambda \text{ off } T_{bt} + \lambda \text{ on } T_t) E \leq 1 - N , \tag{2}$$

where

λ off = $\frac{1}{\text{MTBF (off)}}$ = nonoperating system failure rate

λ on = $\frac{1}{\text{MTBF (on)}}$ = operating system failure rate

T_{bt} = time between checkouts

T_t = checkout interval which here, by definition, equals MTTR

Furthermore, if it is required that S fraction of all missions be completed successfully, then

$$(1 - E) + \lambda \text{ off } T_{tm} + \lambda \text{ on } T_m \leq 1 - S, \tag{3}$$

where

T_m = mission duration

T_{tm} = time from the completion of the checkout to the beginning of the mission

Since an integrated tester is being considered and the election is to perform a checkout just prior to each mission T_{tm} goes to zero. Rewrite (3)

$$(1 - E) + \lambda \text{ on } T_m \leq 1 - S. \tag{4}$$

Solving (4) for E,

$$E \geq S + \lambda \text{ on } T_m . \tag{5}$$

Solving (2) for α ,

$$\alpha \leq (1 - N) - [\lambda \text{ off } T_{bt} + \lambda \text{ on } T_t] E . \tag{6}$$

From the definition of availability (1),

$$\frac{T_{bt}}{T_t} = \frac{A}{1 - A} ; \tag{7}$$

also, if T_{bm} is the time between missions, then

$$T_t = T_{bm} (1 - A) . \tag{8}$$

Substituting (7) and (8) into (6),

$$\alpha \leq (1 - N) - E T_{bm} [A \lambda \text{ off} + (1 - A) \lambda \text{ on}] . \tag{9}$$

Equations (5) and (9) can be used to specify the tester requirements and to show the possible tradeoffs between system MTBF and tester quality.

For illustration, take a hypothetical case with the following requirements:

$A = 0.95$

$S = 0.9$

$N = 0.95$

$T_m = 2$ hours

$T_{bm} = 24$ hours

To simplify the problem, assume that λ off = 0.01 λ on

Then, substituting above values into (5) and (9),

$$E \geq 0.9 + 2\lambda \text{ on} \qquad (10)$$

$$\alpha \leq (1 - 0.95) - 24\,E\,[\,(0.95 \times 0.01\,\lambda \text{ on}) + (1 - 0.95)\,\lambda \text{ on}\,]$$

$$\leq 0.05 - 1.43\,E\,\lambda \text{ on}\,.$$

Equations (10) and (11) are plotted against $1/\lambda$ on in Figure 3. From the graphs it can be seen that, even with perfect testing, the MTBF of the whole aircraft would have to be more than 30 hours to provide the desired availability. If the aircraft MTBF is 100 hours, then $E \geq 0.92$ and $\alpha \leq 0.035$. Observe that, for a small degradation of tester performance, a large penalty, in the form of a longer system MTBF requirement must be paid.

CONCLUSION

The importance of a good maintenance concept to the attainment of high system availability cannot be overemphasized, considering the limits of reliability that can be achieved in today's systems.

The best way to develop a good maintenance concept is to consider maintainability from the inception of system development.

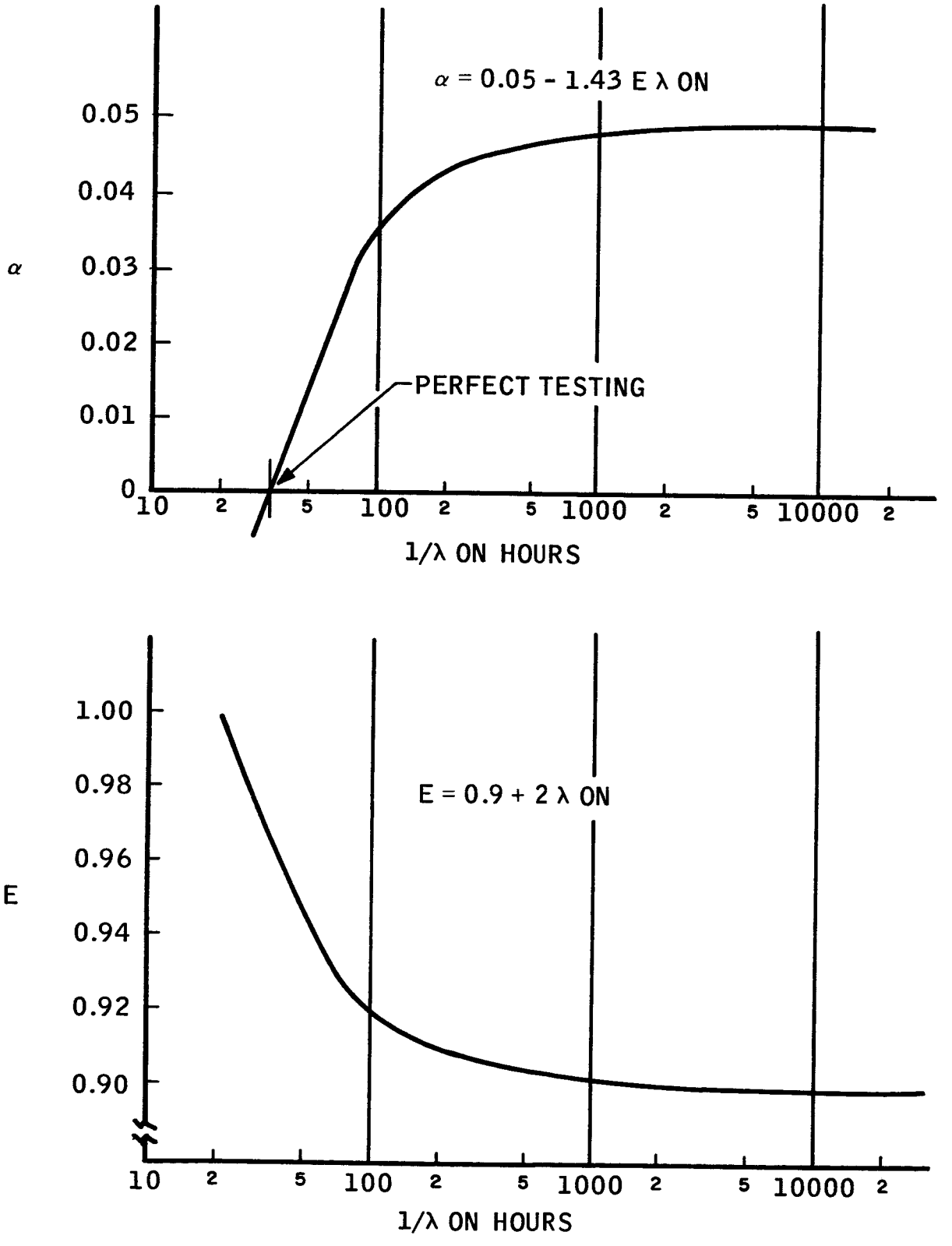

Figure 3. Plots of α and E for the Example

VATE -- DESIGN AND OPERATIONAL CHARACTERISTICS

Victor Mayper, Jr.

VICTOR MAYPER, JR., Hughes Aircraft Company.

Dr. Mayper received his BS and PhD degrees (M.I.T.). He has worked on microwave magnetrons and low-temperature physics at the M.I.T. Research Laboratory of Electronics; on field engineering of a telemetry system for nuclear-weapons-effects measurement; and on new methods of geophysical prospecting for minerals. Since 1955, he has been associated with Hughes Aircraft Company, working on logical design, computer test equipment, system self-tests for various systems, and the design and application of automatic test equipment and systems. His publications include papers on noise in magnetrons, second sound, and induced-polarization prospecting, and he has lectured at U.C.L.A. Dr. Mayper is a member of Sigma Xi, American Physical Society, IRE, and ACM. Present position: Assistant Manager, VATE Systems Department.

VATE -- DESIGN AND OPERATIONAL CHARACTERISTICS*

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I. Introduction and Historical Background

II. The VATE System

III. The "Standard" Consoles (HCM-111)
   1. The Computer Station
   2. Standard Portions of the Test Stations

IV. Programming

V. Adapter Portions of the Test Stations

VI. Typical Adapter Description

VII. Operator-Machine Interaction

VIII. VATE Maintenance and Self-Test

I. INTRODUCTION AND HISTORICAL BACKGROUND

In 1960, the U.S. Air Force Logistics Command came to the decision that depot maintenance of inertial guidance systems should be performed within the Air Force, at a single centralized Special Repair Activity. Government-owned facilities at Newark, Ohio were chosen to house the SRA (and also a new central calibration and standards laboratory for the Air Force). The activity is now known as the Newark Air Force Station, and it is under control of the Middletown Air Materiel Area, Olmsted Air Force Base, Pennsylvania.

Early in the program, the Air Force came to two conclusions:

(1) Automatic testing was mandatory, at least for the major part of the projected work load. The large amounts of equipment destined to flow through the depot, combined with the severe trained-manpower problem and the complexity and precision of inertial-guidance tests, forced this conclusion.

*The work was performed in connection with USAF contract #33(604)-38446.

(2) Test equipment must be applicable to different types of prime inertial-guidance systems with an absolute minimum of modification. In the past, it had been customary to buy "peculiar" test equipment for each make of prime system. When a new prime system entered the Air Force inventory, completely new test equipment had to be procured, and personnel had to be largely re-trained. The penalties in money and efficiency associated with this process produced a heavy pressure for inter-system "versatility" in the test equipment.

A subsidiary conclusion soon reached was the desirability of computer control for the automatic test equipment, because of the complexity of the prime equipment, the trained-manpower problem, and the detailed level of fault isolation required. Finally, since it appeared practical and would be expected to save money, the Air Force concluded that the system should allow one computer to control several different test stations simultaneously, with each test station operating independently, perhaps on totally different tests.

In early 1961, the Air Force contracted for a number of studies as to (1) the best way of implementing the basic VATE (Versatile Automatic Test Equipment) concept of an automatic test system involving shared digital computer control, and (2) the best way of applying this basic concept in "versatile" fashion to the five inertial guidance systems then destined for the SRA (Hound Dog, Atlas, Titan II, Minuteman, and Skybolt), and to possible future inertial guidance systems. Following the study phase, the Air Force concluded that Hound Dog and Atlas were too far along to benefit from VATE, and narrowed the field to Titan II, Minuteman, and Skybolt. In late December, 1961, Hughes Aircraft Company was selected to develop, program, manufacture, and install the system.

The system design is not limited to depot testing or to inertial-guidance testing. The majority of the equipment is general-purpose in nature and militarized, and is suitable for field, depot, or factory testing of almost any prime equipment.

II. THE VATE SYSTEM (AN/USM-176)

The VATE System provides complete fault detection, fault isolation to the plug-in card or inertial component, and acceptance testing of complex airborne inertial guidance equipment. The test equipment essentially implements the knowledge and experience of a small group of highly skilled engineers, but may be operated in a manner compatible with the lesser training and experience of supporting personnel. The implemented skill and functions can readily be changed to match variations in depot "throughput" and equipment requirements. To a large degree, the equipment, methods, and procedures have been standardized to make the system versatile and efficient and to minimize personnel requirements.

In normal operation (Fig. 1), the major input to the VATE system consists of prime systems to be tested. The systems come either from the field or from the repair operation. The major outputs are faulty prime systems accompanied by automatically-derived fault analysis and repair instructions, re-certified operable prime systems, and prime system calibration data.

The VATE System includes a number of small, high-capacity, general-purpose digital computers to control the operations and to evaluate the test results of test stations connected to the prime equipment. Each test station, and the portion of the computer program assigned to it, is tailored to the requirements of a basic type of prime equipment (such as a Titan Inertial Measurement Unit).

Two concepts are basic to the system: (1) One computer controls several (up to eight) test stations simultaneously, and (2) test stations are made up of standard input-output elements, plus a minimum amount of adapter equipment, arranged to match the prime equipment requirements. Each computer and its satellite test stations are called a VATE Group (Fig. 2). VATE Groups are assembled or rearranged as necessary to match depot requirements.

Each test station contains a standard input/output console, a standard operator's console, and adapter equipment. Prime equipment connections are made through the adapter. The "standard" equipment is that portion which is of a general purpose nature, such as the control computer; the operator console; the voltage, resistance, digital, frequency, and time measurement devices; and the voltage, digital and on-off outputs. This equipment is required for practically any reasonably complicated testing task. The "adapter" equipment is that portion which is required only for the particular task at hand, such as power supplies for the prime equipment, special digital buffers, rotary tables, autocollimators, and the like.

Because of the versatility of the standard equipment, the need for special adapter equipment is kept to a minimum. In addition, the VATE adapter equipment is constructed largely of general-purpose modules and subassemblies (some of which are also used in the standard equipment). They can be removed and re-connected to form other adapters. Thus the VATE system maximizes re-usability of test equipment.

Automatic time-sharing of the control computer permits independent operation of up to eight test stations per computer, attached or detached at will. The computer retains full control of each test station, but may execute a different program for each test station. In effect, the computer looks at each test station in turn repetitively, rapidly enough to appear to exercise continuous control. Test stations momentarily not

requiring attention are skipped to permit maximum program performance on the remaining stations. To each test station operator, it appears that he has a computer to himself, and his control-display console communicates directly with the computer. The operations being performed on his prime equipment need bear no relation to the operations being performed simultaneously at other test stations.

For this reason, only a small fraction of the total cost of the control computer is chargeable to each test station. Most of the test station cost is the input-output equipment and the adapter.

The required quantity of each type of VATE test station is determined by the average unit test time and the depot "throughput". The quantity of VATE computer stations required is determined by the number and complexity of test stations. For example, if 12 Minuteman system test stations were required, two VATE computer stations would be required, providing capacity for four more test stations of another type.

III. THE "STANDARD" CONSOLES (HCM-111)

The standard control computer and the standard portions of its associated test stations are designated the HCM-111 automatic test system, and are designed to meet MIL-T-21200, Class 3. They will serve as the control equipment for any complex automatic testing task. In Fig. 2, the HCM-111 portions are shown more heavily shaded. The HCM-111 for a single test group includes:

(1) A control computer console

(2) Its associated magnetic tape console

(3) One to eight standard input/output consoles

(4) A like number of standard operator's control/display consoles.

On a particular set of tasks, adapter equipment must be supplied as an additional part of each test station.

The designation HCM-111 implies a group of variable size, depending on the number of test stations. The four types of consoles may be further grouped, as follows:

(1) The Computer Station (one per group), composed of the computer console and the magnetic tape console.

(2) The Test Station Standard Equipment (one to eight per group), each set composed of an input/output console and an operator's control/display console.

1. The Computer Station (AN/UYK-2)

The Computer Station (Fig. 3) is the heart of each VATE group. It controls and evaluates the testing process at each of the separate Test Stations in rapid and automatic cyclic sequence.

The AN/UYK-2 computer is a medium-speed, high-capacity, general-purpose digital computer, optimized for real-time control and time-shared automatic testing functions. The requirements for a large, reliable, economical, militarized internal memory, with minimum transient sensitivity and preferably nondestructive readout, led to the choice of a 40,000-word magnetic drum for basic memory, supplemented by a number of magnetic-core shift registers for quick-access temporary memory.

A versatile "2 + 1" -address order code is used, designed to facilitate automatic or manual minimum-latency programming. Further to facilitate programming, all electronic input-output actions at the test stations are performed by direct commands; for example, one program command causes electronic selection of a particular analog input, conversion to binary, and use of the result in a 2-address arithmetic operation. Direct-command input-output also has the desirable effect of almost eliminating digital input-output buffering.

Circuit functions are mechanized on individual circuit cards. The cards are interconnected through unit and console wiring to implement the computer function. Silicon semi-conductors are used exclusively, in circuits designed with wide "worst-case" margins for military extremes of environment, power supply, and aging. The mechanical design emphasizes ruggedness and accessibility. Half-width slide-out vertical drawers are used to provide access both to plug-in cards and to wiring, and standardized flexible ribbon-conductor cables permit operation with units slid out, without extender cables or cable-flexing devices.

Two magnetic tape transports are included in each magnetic tape console. One transport contains an IBM-compatible tape with additional computer program material. This may be read, under computer control, into a reserved portion of the computer program memory, to provide capability for future expansion of programs beyond the size of the internal memory. The same transport and electronics may be used to supply automatically any required memory-loading signals to prime guidance computers under test (e.g., Minuteman D17B), when the test requires reloading the guidance-computer memory. Finally, this transport is used for initial loading or changing of the normal operating computer program, stored on the memory drum.

The other transport is used to record data for processing by other equipment. Information is recorded in standard IBM

200-bit-per-inch format. Information such as reliability and test-significance data may be obtained from this taped record.

When required by the characteristics of the prime equipment, a paper-tape punch is also included. This permits the VATE system to produce automatically the calibration tapes (and other program material, if required) for guidance systems that use such tapes.

For application where the extreme information capacity of magnetic tape will never be required, a (detachable) paper-tape reader may be substituted for the program magnetic-tape reader.

All communication between the computer station and each of its several test stations is digital, by means of transformer-coupled balanced lines. This eliminates information degradation between the computer station and the test stations, reduces the quantity of analog buffering, and eliminates large ground-loop problems. During the period the computer is servicing one test station, automatic logic directs all Input/Output commands to that particular station.

The computer station operates unattended, except for start-up, which involves "computer power", "self-test", "operate", and "proceed" pushbuttons.

A manual control panel (normally covered) is built in for detailed control, display, and communication between a human and the computer. The principal use of this panel is in system development, for checkout and modification of the program. It is also used in some HCM-111 troubleshooting operations.

A subunit tester, for checking and troubleshooting individual circuit cards, is also built in.

2. Standard Portions of the Test Stations (AN/USQ-33)

Each test station contains a standard Input/Output Console, a standard Operator's Console, and Adapter equipment. The standard equipment is described below, and the adapter equipment is described in Section IV.

Input/Output Console:

The Input/Output Console (Figures 4 and 5) provides the basic input/output adaptability of the test station, accepting signals external to the digital computer and converting them into binary form, or converting binary signals from the digital computer into a form suitable for external use.

The Input/Output equipment may be adapter to any desired prime system by altering the test programs recorded in the computer and providing adapter equipment. All components,

circuits, and subassemblies of the Input/Output equipment are standard for any application.

The console has the following input/output capability (all accuracies noted include effects of aging and the specified environment):

Inputs:

The input capability is divided into two major areas: the electromechanically selected inputs, and the electronically selected (high-speed) inputs. The electromechanically selected inputs cover a wide range of voltages and functions, and are set up by fast-acting reed relays under program control. The electronically selected inputs, of necessity, have a somewhat narrower range of voltages and functions, but are addressed directly by computer program commands and operate at a speed directly compatible with program operations. The two areas complement each other, to provide a complete computer-controlled automatic-testing capability.

The electronically selected inputs are shown in Table 1. They include dc voltage (±0.02%, ±8 volts), on-off or parallel digital, serial digital, and priority-request lines.

The electromechanically selected inputs are selected by a reed-relay matrix. The matrix selects two floating differential pairs from up to 560 pairs at the input connector (expandable). Each of the two selected input pairs is in turn directed to one of the following:

1. A 2-channel voltage/resistance/on-off signal conditioner
2. A frequency/time/count/waveform converter
3. A pair leading out of the console (and, back in again, if external wiring so directs), to permit using the reed-relay matrix to select inputs for special external signal-conditioning devices (e.g., a hipot tester or thermocouple amplifier).

Some modes of the two built-in conditioners require both pairs at once, and some require only one pair. For modes requiring only one pair, each pair is independent of the other, permitting two simultaneous independent electromechanically-selected measurements.

The voltage/resistance/on-off differential signal conditioner capabilities are shown in Table 2. It measures dc voltage, ac in-phase voltage, ac quadrature voltage, resistance, on-off condition, ratio, and phase. AC voltage measurements maintain full accuracy from 50 cps to 5 kc, and 1 percent accuracy to 10 kc.

The frequency/time/count/waveform converter is composed of an assembly of counting registers, pulse generators, amplifiers, and Schmitt triggers that may be programmed into various counting and timing modes. The converter has the properties shown in Table 3. It has five basic pre-wired modes: high frequency, low frequency, count totalizing, waveform, and delay (relationship of two different waveforms). In addition, it includes provision for a plug-in patch box to facilitate specialized modes, such as jitter measurement or multiple simultaneous up-down counts.

Outputs:

The output capability time-shares much of the input electronics, and provides both digital and d-c analog outputs. (Since the scale and frequency requirements for a-c outputs are variable, a-c outputs are provided by installing modulators, driven by d-c outputs, in the adapter. Standardized modulator subassemblies are available for the situations so far met within VATE.)

The d-c analog outputs have the properties shown in Table 4. They cover the range ±8 volts dc, and slew at up to 7000 volts per second under program control.

A number of different forms of digital outputs are provided. Serial digital outputs are provided both from the computer logic and from the magnetic tape, and parallel digital outputs are provided that can drive either relay/lamp loads or precise logic loads. Their various properties are shown in Table 5.

Operator's Console:

At each test station, a standard Operator's Console (Fig. 6) is provided. It includes a pushbutton control panel, a numerical display panel, an alphanumeric printer, and a computer-controlled slide projector.

Controlling functions are performed by manual activation of pushbuttons on the control panel (Fig. 7). The buttons (except "emergency shutdown," "reset," and keyboard entry controls) illuminate to provide information on computer program status.

A Printer unit is adjacent to the Control Panel. It records all pertinent test data, operator-entered data, repair instructions, and other alphanumeric information, under program control. It provides 20 columns of 64 letters, numbers, and symbols, and operates at speeds up to 10 lines per second.

A Random Access Slide Viewer provides selection, under program control, of 508 different 35-mm slides, and projects them on a viewing screen directly above the display panel.

This accelerates testing and eliminates much operator error on manual actions.

IV. PROGRAMMING

Programming the digital computer for VATE differs from programming a scientific or commercial computer. The program design is intimately involved with the design of the adapter equipment and the test methods, and with the equipment characteristics of the system under test and the HCM-111. To perform a truly automatic test, it is often necessary to take account of detailed timing relationships and prime and test equipment characteristics, which would be of no concern to a scientific or commercial programmer. Furthermore, since the program is a vital part of the system, the program designer should be a member of the basic design team, to obtain an optimum overall system design. For this reason, an automatic-test program designer should have a strong engineering background and a thorough understanding of the prime and test equipment.

Programs for VATE are developed at Hughes principally by engineers with programming training, rather than by scientific or business programmers, because it appears more practical to teach an engineer programming than to teach a programmer engineering. Some programming specialists are also employed, for cooperation on difficult programming problems, and for work on general-purpose programs such as coding aids and service programs.

The main task of the program design engineer is to help solve the system design and checkout problem. He must work with and complement the system design engineer in the adapter and test design, and derive a detailed step-by-step description of the program actions. He must then perform the relatively minor task of turning this description into an actual computer program. Finally, he must again work with the system design engineer in the difficult and demanding task of system checkout, to be sure that the final system (program plus equipment) satisfies its requirements.

Although the task of making a coded program from the step-by-step description is normally a minor and relatively routine portion of the total effort, it is still a significant one, and should be minimized for reasons of cost, schedule, and engineer morale. Therefore, Hughes is supplying as part of the VATE system an extensive coding-aid package specifically designed for automatic-test programs, to operate on data-processing machines.

The coding aids include:

1. A versatile automatic record-keeping and updating system, which allows good control of the hundreds of thousands of program

orders in the several computers of the VATE system, and yet permits flexible and rapid changes and intermixing.

2. A simulator and trace program, with flexible operation, input, and tracing control, to permit preliminary off-line checkout of VATE programs.

3. An assembler-compiler, which permits arbitrary mixtures of pseudo-machine language (in mnemonic code), simplified assembly language, and macro (compiler) language. The assembler-compiler provides excellent program optimization, based on the special real-time and input-output requirements of the VATE system and other HCM-111 automatic test systems. (It provides both a memory-loading tape and a detailed printout, showing exact relationships among source-language inputs and machine-language outputs. Thus the final system checkout, which inevitably involves console operations and machine language, will not suffer from the fact that initial coding was not in machine language.)

In addition to the coding aids, a number of standard programs and closed subroutines are provided as standard equipment in the operating HCM-111 computer memory. These include the self-test programs, the "library" routines, and the service routines. Together, these occupy about one third of the memory, leaving two thirds for specialized system programs. (The system programs, of course, make considerable use of the library and service routines, as subroutines.)

The self-test programs qualify the complete HCM-111 system automatically, and self-isolate any failure to one (or at most a few) standard plug-in subassemblies. (See below, Part VIII.)

The library routines supplement the arithmetic and data-processing capability of the basic order code; for example, by performing double-precision arithmetic, making binary-gray code and binary-decimal conversions, performing waveform analysis on stored sampled waveform data, etc.

The service routines remove routine input-output, evaluation, sequencing, time-sharing, and executive supervision from the task of the system programmer. Among the many functions provided by the standard service routines are:

- Time-sharing of the computer among the test stations. This routine operates in conjunction with a small amount of built-in logic, and provides a number of modes, depending on the time requirements of the individual test stations at any instant.

- Sequencing from one test to the next, as directed by the system-test program; and sequencing among portions of an individual test which occupies more

than one time-sharing cycle. This routine also permits operator control of the testing sequence; interprets the various options as to level of testing, repeating, hold condition, etc.; and processes priority request from test station.

- Operator data entry, such as manually-selected branching options, results of manual test observations, and numerical data such as unit serial numbers or written log data.

- Operator control entry from control pushbuttons.

- Complete performance of straightforward measurement-and-limit-check tests, including selection of input, ranging and function selection, measurement, check against limits, display/print/record results, "Hold" and display viewer slide if required, branch depending on test results, calculate if necessary, etc. This routine performs essentially the same functions as the usual sort of tape-controlled "automatic tester," although it provides certain additional capabilities such as phase angle calculation, block continuity checks, and special dynamic "Hold" conditions during waiting periods.

- Selection, ranging, and measurement of electromechanically-selected inputs for processing by system programs.

- Semimanual operations, controlled by the operator's keyboard, in which the system and its operator displays are used as a digital voltmeter, phase meter, frequency meter, or time meter; or as a generator of manually-commanded d-c voltages or sets of digital on-off conditions. The operator selects both the function and the test point to which it is applied.

- Control of peripheral devices such as the printer, slide viewer, and numerical displays at each test station, and the magnetic tape transports at the computer station.

V. ADAPTER PORTIONS OF THE TEST STATIONS

In any large automatic test system, the adapters are a major part of the installation. Their complexity is reduced by the presence of computer control, but the VATE test stations still include considerable adapter equipment. To avoid problems of classification, the following discussion will be rather general.

A typical adapter used in the VATE system for testing and troubleshooting a complex inertial guidance system may include much of the following:

- Power supplies for the prime system
- Power supplies for the adapter itself
- Air and/or water coolers for the prime system
- Special signal switching relays and power controls
- Special signal conditioning and buffering equipment, especially for digital signals which are too fast to use the normal Input-Output Console circuits and program control
- Loop-closing amplifiers, especially when testing analog equipment separated from its own servo electronics
- Automatic autocollimators for optical alignment measurements
- A test stand fixture, or an automatically-controlled rotary table, to support the prime equipment
- A taper-pin patch bay, to provide wiring flexibility for changes and improvements, both in the prime system and in VATE
- A "breakout" or junction box for tapping into prime signals and mounting isolation devices for signals critical as to lead length

Typically, the total cost of an adapter for complex systems such as Minuteman or Titan is between 60% and 110% of the cost of the Input-Output Console. It occupies two or three 19-inch bays 5-feet high (sometimes including one complete bay devoted to the flexible taper-pin patching) for electronics, plus part of a bay for air/water coolers, plus the test stand or rotary table (with associated autocollimators), plus one bay of table electronics if the rotary table is used.

For simpler systems, the adapter is much less complex. Also, in this case, it is possible to use "extended time-sharing", in which a single Input-Output Console is time-shared among several Test Sub-Stations, in exactly the same way that the Computer Station is time-shared among several Test Stations. Sub-station time-sharing reduces the cost allocation for "standard" equipment, to the point where it is again comparable with the cost of the simpler adapter.

The most important part of the "versatility" of the VATE system comes from the standard nature of its "standard" portion. The standard portion, accounting for well over half the manufacturing system cost, is adaptable to new

prime systems without hardware change. However, the requirement for "versatility" has been carried over into the adapter design as well. Each type of adapter is necessarily different, but a number of major units (power supplies, automatic precision rotary table, etc.) are identical among various adapters. The entire design of the adapter is based as much as possible on the standard sheet metal, subassemblies, and plug-in circuit cards. (Those portions identical to "standard" elements are, of course, designed to MIL-T-21200. The more specialized adapter elements are designed similar standards of quality, but to less severe environmental requirements.) As a result of the attention paid to this problem, the VATE system hardware is re-usable on almost any type of new prime system.

VI. TYPICAL ADAPTER DESCRIPTION -- MINUTEMAN PLATFORM

One of the several types of adapters in the VATE system is the Minuteman Platform Adapter Set (AN/GSM-98). It is more or less typical of the other adapters, and makes a good example because it includes digital functions, analog functions, electromechanical functions, and auxiliary functions.

1. Function and Outline Description of Minuteman Platform Test Stations

Testing of a Minuteman system begins and ends at the Minuteman System Test Station. At the System station, the complete prime system is tested and qualified to a test specification. If a fault exists, it is isolated as far as possible there, with the system in its assembled configuration.

For a large fraction of the faults, the faulty module may be isolated and replaced at the System station, without disassembling the system. This is true of all faults in the platform electronics and power supplies, about 50% of the faults in the computer, and a smaller fraction of the faults in the platform mechanical assembly.

For the remaining faults, test access in the assembled-system configuration is insufficient for practical automatic fault isolation. Instead, the fault is isolated at the system station to the platform assembly or to the computer, and the platform or computer is then removed from the system for more detailed fault isolation. The computer assembly is finally fault-isolated and repaired at a Minuteman Computer Test Station, and the platform assembly at a Minuteman Platform Test Station.

At each Minuteman Platform Test Station, faults in the platform are isolated to the faulty inertial component or other replaceable assembly -- the mechanical analogue of a replaceable electronic module. Examples of assemblies replaced at this

station are gyros, accelerometers, gimbal motors, bubble levels, and the like. Acceptance testing of the platform assembly is also performed at this station, after repairs, as a necessary prerequisite to re-installing the platform in a system, for system acceptance testing.

The Test Station is shown pictorially in Figure 9.

The Input-Output and Operator's Consoles form the AN/USQ-33 Test Station Standard Equipment, standard for all types of test stations. The remaining items -- Environmental Control Console, Holding Fixture Group, and Adapter Electronics Console -- constitute the AN/GSM-98 Minuteman Platform Adapter Set. The Fretime Patch Unit is physically mounted with the Standard Equipment, but is actually also part of the Adapter Set.

The Environmental Control Console (419006) contains the coolant source required for the prime equipment. The basic console mounts both an air cooler and a liquid cooler, and is standard for all stations. Some stations require both coolers, but some (such as this one) require only one or the other, and in the latter case the unused cooler is omitted.

The Platform Holding Fixture (419137) mounts the platform, and provides for physical motion of the platform, necessary for certain gimbal-servo tests. Associated with the fixture are certain items of auxiliary equipment, such as the thermal cover to provide thermostatted, circulated ambient air for critical measurements, and the plumbing connections to the water cooler.

The remaining major item in the diagram is the adapter console proper, with its associated cabling and Fretime Patch Unit.

2. The Adapter Electronics

The Adapter Electronics Console (419130) and Fretime Patch Unit (419138) contain the electronic portions of the Minuteman Platform Adapter Set.

The basic electronics console is standard for all Minuteman and Titan adapters. Only the internal wiring differs from one to another. (The advantages of this standardization are great enough to far outweigh the minor waste of volume implied by the four small blank panels in the console.) It is composed of three bays, each with a standard 19-inch panel width and approximately 5-foot panel height. The three bays are rigidly connected, and mounted on a single combination fork-lift and caster base for mobility.

The left-hand bay of the console is taken up almost entirely by a large field of taper-pin patch blocks. Leads from the Input-Output Console are brought to the back of one half of

the patch field. Leads from the prime equipment and the adapter units are brought to the back of the other half of the patch field. Almost all interconnections among prime equipment, adapter units, and Input-Output Console are made by shielded patch connections on the front of the patch field. This provides a high degree of flexibility for interconnection changes, due both to prime-equipment changes and to system integration checkout. The interconnection changes are made rapidly and with minimum risk to wiring integrity. (This feature has already paid for itself in both cost and schedule savings.) Although this particular adapter does not require all the patch points available, basic patch bay standard among all adapters has been used.

The electronic portions of the adapter are packaged in half-width slide-out drawers, connected to the console by ribbon cables to permit extending while "hot". The drawers are half-height instead of full height, permitting flexible "mixing" of half-width and full-width drawers in different adapters, but otherwise are similar to those of the Standard Equipment.

The four drawers (and Fretime patch unit) have the general functions of supplying power, performing specialized switching, exciting pickoffs, closing servo loops, shaping and re-levelling of digital pickoff signals, and counting digitally the gimbal positions and accelerometer outputs.

The Platform Electronics drawer (419131) contains mostly loop-closing amplifiers. Amplifiers are required for the three gimbal motors, the three accelerometer motors, the four gyro torquers, and the four gyro pickoffs. Circuits are also required to provide excitation for gyros and pickoffs. Because of the necessarily special nature of the circuits, circuits similar to those in the prime platform electronics are used.

The Digital Signal Conditioning drawer (419134) amplifies, shapes, and relevels the signals from the digital gimbal and accelerometer pickoffs and the bubble levels. These signals are then delivered to the Fretime patch unit for counting, or directly to the Input-Output circuits for digital sensing.

The Adapter Power Converter Unit (419114) is a power supply standard to all Minuteman and Titan adapters. It provides a set of regulated and unregulated dc voltages for operation of the adapters and prime equipment. It includes safety circuits for overcurrent, overvoltage, and undervoltage conditions.

The Power Control Unit (419132), as its name implies, contains the specialized switching circuits used by the computer to control power sequencing in the adapter and prime equipment. In addition, it contains the switching isolation devices necessary to make continuity and resistance measurements on sensitive circuits.

The Platform Fretime Patch Unit (419138) is mounted physically in the Input-Output Console, but is functionally a part of the adapter. This unit contains logic circuits and wiring which connect adapter to the multiple registers in the Input-Output frequency/time circuits. As a result, the six continuous up-down counters (three gimbal pickoffs, three accelerometers) may be mechanized by six of the eight magnetic shift registers in the Input-Output. Considerable digital adapter equipment is thus saved, and computer access to the instantaneous value of each count is facilitated. (The remaining two registers remain available for standard frequency/time/count/waveform measurements.)

VII. OPERATOR-MACHINE INTERACTION

Practically all interaction between the operator and the machine is conducted via the standard Operator's Console (Figures 6, 7 and 8). The operator sends information to the computer by pressing the pushbuttons on the control panel. The computer sends information to the operator by (1) illuminating the pushbuttons or other annunciators, (2) displaying numerical information on the decimal displays (Figure 8), (3) recording alphanumeric information on the printer, or (4) displaying a slide on the random-access slide viewer. This combination of communication devices permits rapid man-machine communication, with an extremely low error rate.

A typical test sequence might run as follows:

The operator presses the Station Power and Adapter Power buttons. The buttons glow amber to indicate that the turn-on sequence has begun but is not complete. When the respective programmed sequences are complete, the buttons glow white.

The operator then presses the Operate button, to inform the computer that the station is ready for computer controlled operation. This also glows amber until the computer finishes setting up initial conditions for the station, then glows white, indicating that the computer has accepted the command. A slide then appears, telling the operator how to enter his identification number and the prime equipment serial number.

The operator enters these numbers on the keyboard. The computer stores the information, and prints it as a heading, along with the station number, time, and date. (For prime equipment which comes in several variations, depending on block or serial number, the computer uses the stored equipment number to determine automatically which tests to perform.) A slide then appears, giving him (1) set-up instructions, (2) the permissible starting places for a test of particular prime equipment, and (3) the procedure for entering the test start number (and test stop number, if desired).

At this time, the Hold button and the Operator Action annunciator are illuminated white. The Test Step, Subroutine, and Routine buttons are illuminated blue, indicating they are ready to accept commands.

Next, the operator enters the desired test number for the start of the test. He presses the Test Step, Subroutine, or Routine button, depending on whether he wants a minor part, a major part, or the totality of the test routine. The selected button glows white. He then enters the 5-digit start test number on the serial keyboard, in normal left-to-right order. As he enters it, the digits appear on the Keyboard Entry digital display, providing visual feedback. If the displayed number is correct, he presses the Enter button. The computer then reads the number into the program, and displays it on the Test Number display, providing visual proof that the computer has received the correct number.

If the operator desires the test to stop automatically at some point other than the normal end, the slide instructs him to depress Option A (which is also blue at this time). Option A then glows white, indicating that the number he next enters is the stop test number instead of the start test number.

When a test number has been entered, the computer prints it for record, and illuminates the Proceed and Repeat buttons blue. The operator then normally presses the Proceed. It turns white, the other darken, and the test begins.

As the test proceeds, the operator may observe its progress by means of the changing Test Number display and by means of the slide viewer. Test results and other information are printed to an extent determined by the program (Fig. 10).

If the operator wishes to stop the sequence, he depresses the Hold button. The Hold button glows amber, indicating that Hold has been requested but not yet acted on. The computer continues with the current test until it reaches a safe stopping point (as selected by the program). It then enters the Hold program, illuminates the Hold button white, and presents a slide telling the operator his options.

At this point, the Proceed and Repeat buttons are again blue. The operator may select a new test number, may Repeat continuously all or part of a test, or may merely continue the test by pressing Proceed.

If the program reaches a point where manual action is necessary, it illuminates Hold and Operator Action white, and presents a slide describing the necessary action. If the action involves operator judgement or choice, appropriate Option buttons illuminate blue, to allow the operator to

inform the computer of the result. Only the meaningful buttons are blue; the others are dark. Since buttons may be pressed in combination, the four lettered buttons provide up to fifteen choices. The Manual Go-No-Go buttons allow a contribution from manual tests to automatic fault isolation logic, if necessary.

The above actions are performed almost entirely by the program rather than by wired-in logic. Thus, a high degree of human-engineering sophistication is possible at reasonable cost.

VIII. VATE MAINTENANCE AND SELF-TEST

It is important to the Air Force that the improvements in prime system maintenance attributable to VATE not be counterbalanced by maintenance problems of VATE itself. For this reason, considerable attention was paid to automatic VATE self-test, self-calibration, and self-fault-isolation. Since computer control is present, a high degree of automaticity is feasible in self-fault-isolation.

Self-test and card-level fault isolation are performed by a combination of built-in equipment, computer programs, and external equipment.

The built-in equipment includes first, the usual checks of parity on magnetic-tape and keyboard information, and feedback checks of relay-coil excitation; second, occasional logic gates and analog paths inserted to facilitate programmed self-test; third, voltage, resistance, and frequency standards; fourth, marginal voltage controls; and fifth, a moderate amount of feedback switching and test-relay switching in the adapters. All of these except the most elementary are used in conjunction with computer programs, to save equipment and extract the maximum of information.

Also built-in to the standard equipment is a semi-automatic tester for individual plug-in cards, used in conjunction with fixed procedures and an oscilloscope or VOM. Although it shares power and some signal sources with the operating portions of the console, it operates independently, and is buffered to ensure that faults in a tested card will not interfere with simultaneous system operation.

Programs providing six levels of self-testing are included in the Computer memory:

1. Thorough daily self-tests are run on the Computer Station before system testing begins, and on each Test Station when it is turned on.
2. Self-tests and self-calibrations of a Test Station (with or without prime equipment connected) can be commanded by any Test Station operator without interfering with system testing at the other Test Stations.

3. Self-tests (somewhat less detailed than item 1.) are automatically performed on the Computer Station, whenever the computer is on and no stations require immediate attention. These may also be commanded from a Test Station, without interfering with other Test Stations.
4. Periodic self-tests of a more detailed nature than the above are performed at pre-established intervals.
5. Self-fault-isolation to one (or at most a few) plug-in cards is performed almost entirely automatically, although "cookbook" human actions may be required for certain basic failures which prevent even simple program operation.
6. Particular self-tests may be included as subroutines of the operating system program, whenever the system program designer so wishes.

The external test equipment is used only for the periodic tests. It provides feedback paths from outputs to inputs, to make a 100% check of selection switching and signal conditioning. It also provides a few signal sources and detectors, particularly for the adapters, to permit 100% testing of other circuits. An external device is also used to test non-standard plug-in cards used in the adapters.

The internal standards require occasional calibration to ensure their traceability to Bureau of Standards primary standards. To facilitate this, the standards unit is removable as a whole. For scheduled recalibration, the standards unit is removed and replaced immediately with a freshly calibrated one. The removed unit is then taken to the standards laboratory, where the voltage, resistance, and phase standards are checked. (The accuracy requirements are sufficiently high that a standards laboratory is the most suitable place for this operation.)

In the VATE system as installed at NAFS, frequency standards are supplied from an Atomichron-referenced source in the NAFS standards laboratory, and modified and buffered by a special unit for transmission to the test stations. In separate installations, a frequency standard would be added to the built-in standards.

Analog voltage, dc

Number — up to 128
Range — -8 to +8 volts dc
Overall accuracy — ±0.02% of bipolar full scale
Speed — 6000 samples per second on a single line
4000 samples per second on different lines

On-off (parallel digital)

Number — up to 360
"0" condition — open or greater than +7 volts
"1" condition — ground or more negative than +3 volts
Speed — program reads group of 15 in 160 μsec (90,000 per second)

Serial digital

Number — 1, with provision for address distribution in adapter
Speed — 275,000 bits per second
Format — unrestricted; enabling gate and shift pulses supplied (HCM-111 computer sees a series of 22-bit binary words)

Priority request

Number — 1
"Priority" condition — floating contact, closed
"Normal" condition — floating contact, open

Table 1. Electronically selected inputs.

Maximum voltage — 500 peak

Voltage ranges — ±1, ±2, ±5, ±10, ±20, ±50, ±100, ±200, ±500 v full scale

Types of measurement and accuracies

- Dc volts, ±0.03% of bipolar full scale (500 cps bandpass)
- Ac volts non-phase-sensitive, ±0.3%
- Ac volts in-phase, ±0.2%
- Ac volts quadrature, ±0.2%
- Resistance, 0 to 1M in five ranges; error, ±0.2%
- Ground/open/28 v (on-off response)
- (Other types - e.g., ratio and phase - by calculation)

Table 2. Measurements via voltage-resistance signal conditioner.

Modes: 5 prewired modes are high frequency, low frequency, count totalizing, waveform, and delay

Mode selection: from computer program

Filtering: selected by program

- high pass 0.1, 30, 300, 3000, 30,000, 300,000 cps
- low pass 30, 300, 3000, 30,000, 300,000, 9,000,000 cps

Attenuation: selected by program - 1, 5, 25, 100

Trigger threshold after attenuation — 2 independent, selected by program — -8 to +8 volts, ±0.1 volt

Trigger threshold slope — 2 independent, selected by program — positive or negative

Time resolution — 1 μs

Maximum count rate — 1.1 Mc

Minimum pulse length — 0.2 μs

Table 3. Measurements via frequency/time/count/waveform converter.

Number — up to 32

Range — -8 to +8 volts dc

Resolution — 31 mv per step

Accuracy for arbitrary setting and worst program — ±15.5 mv = 1/2 step

Accuracy, about step position, in normal program — ±5 mv

Slewing speed — 7000 volts per second

Table 4. D-c analog outputs.

Serial digital outputs (one each):

(1) From computer, 1 to 255 22-bit words per block, at computer clock rate; clock and envelope signal supplied.

(2) Directly from magnetic tape at computer station (e.g., to load the memory of a prime guidance computer under test), any number of characters, character rate nominally 1 kc, bit rate within a character equal to computer clock rate; clock and envelope signal supplied.

Parallel digital outputs:

Number — up to 480

Maximum "on" current — 200 ma from positive source

Maximum "off" voltage — +40 volts

Speed — program sets group of 10 in 160 μsec (60,000 per second)

Connection — either to +28 volt return or to logic return, return lead available for each group of 10

Table 5. Digital outputs.

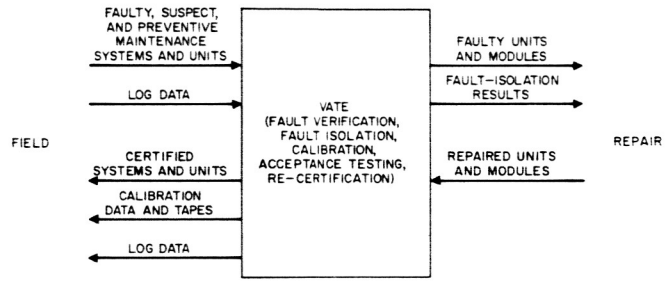

Figure 1. Flow Through the VATE System

VATE GROUP (SYMBOLIC)

HUGHES
HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

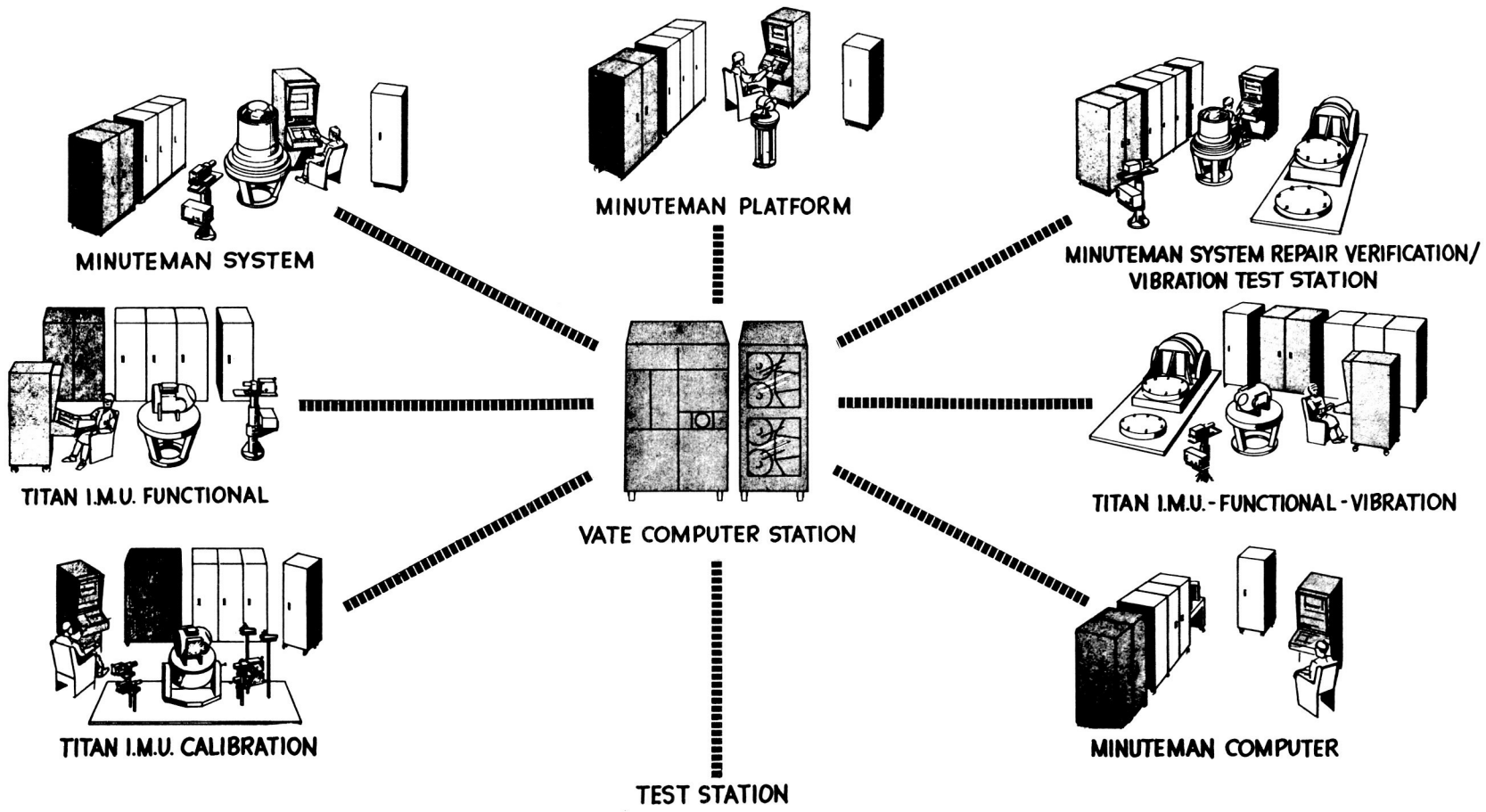

Figure 2.

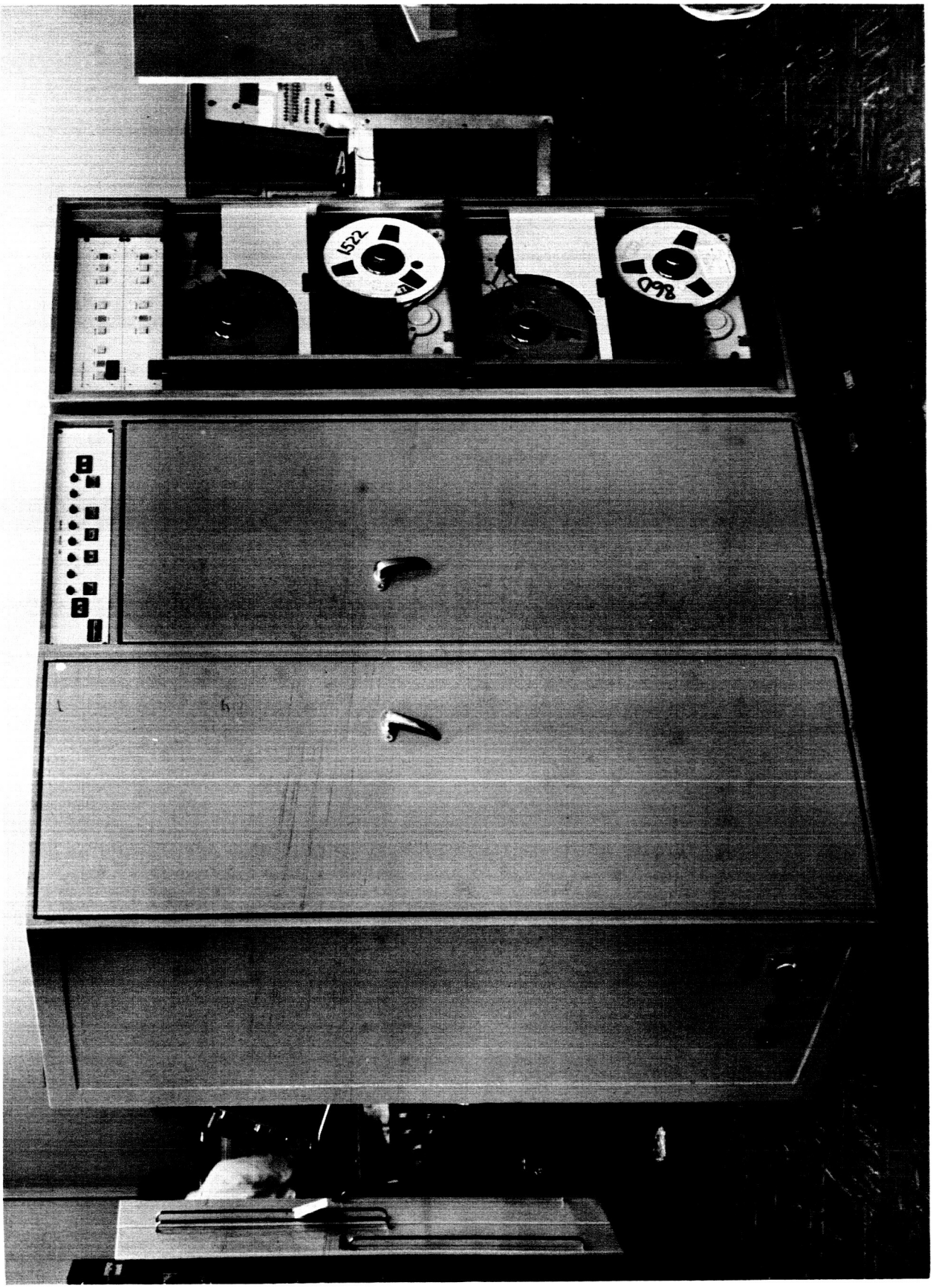

Figure 3. VATE Computer Station

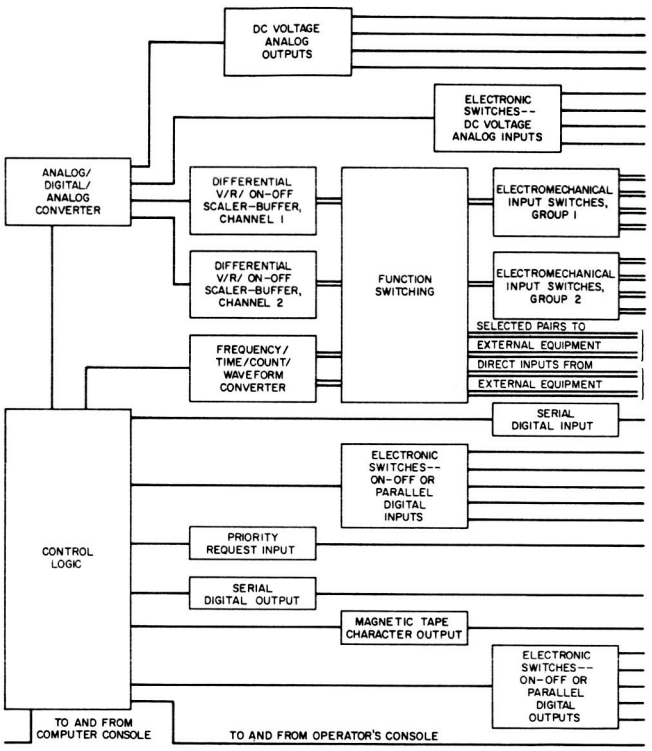

Figure 4. Input-Output Functional Diagram

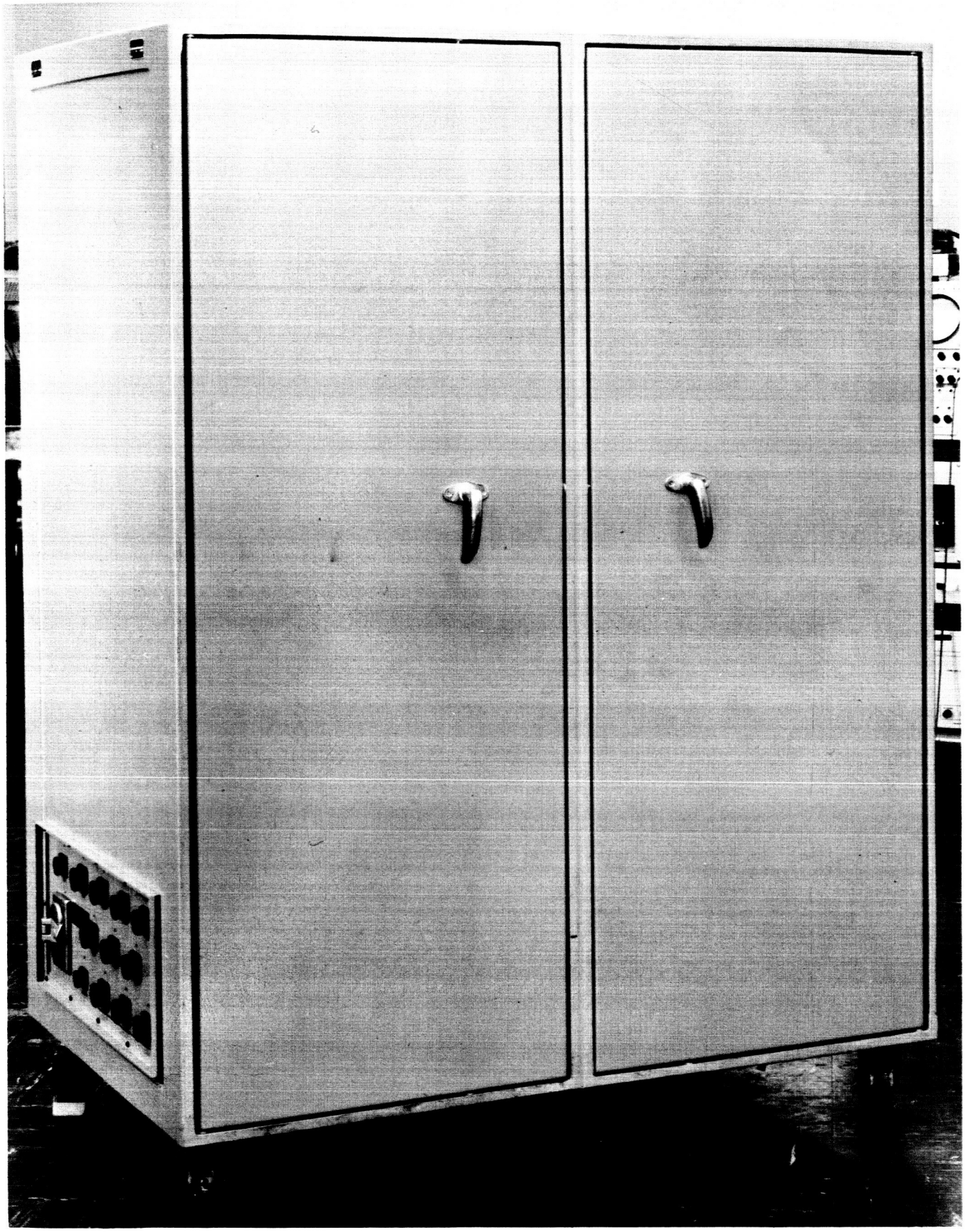

Figure 5. Input-Output Console

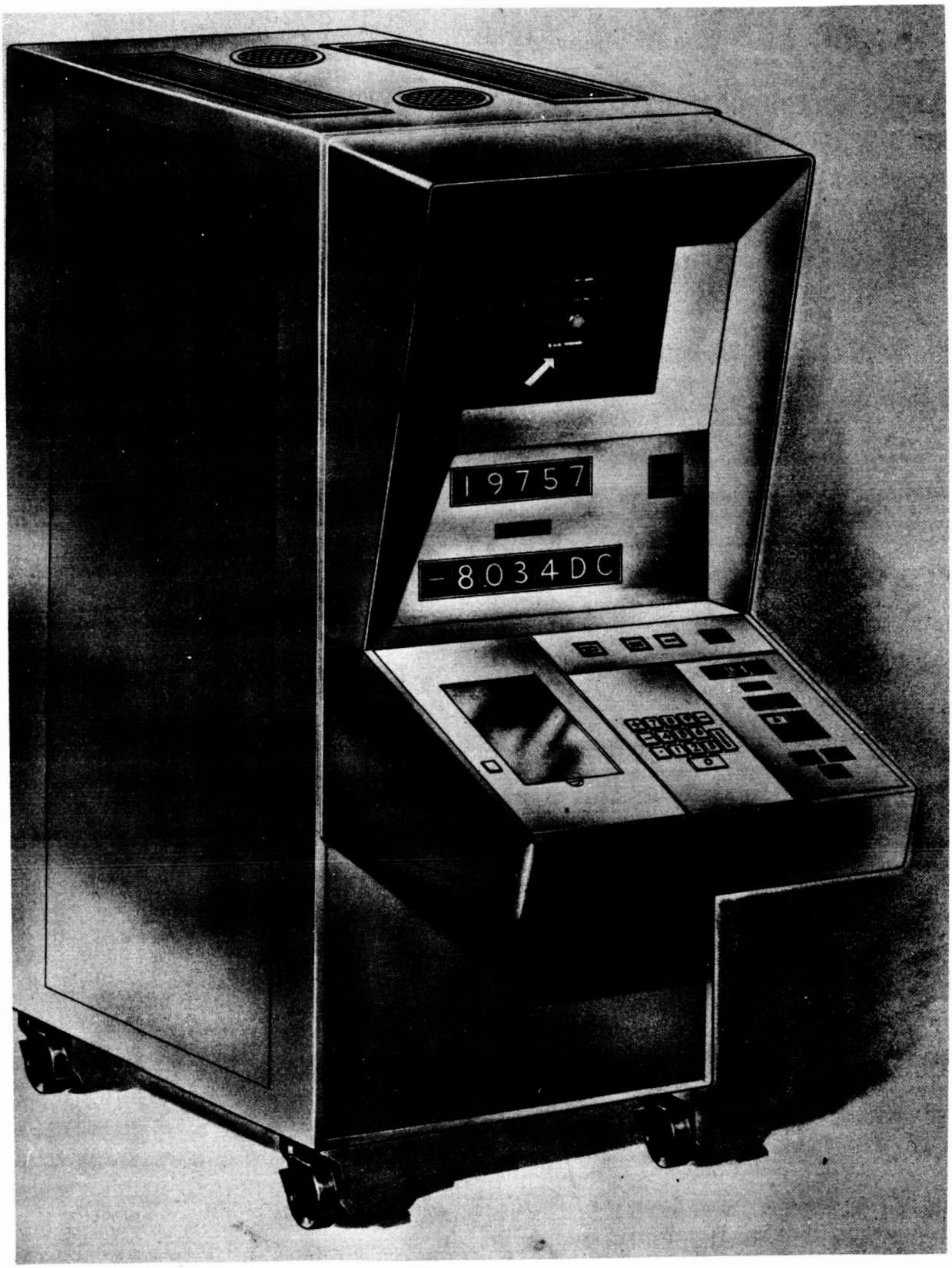

Figure 6. Operator's Console

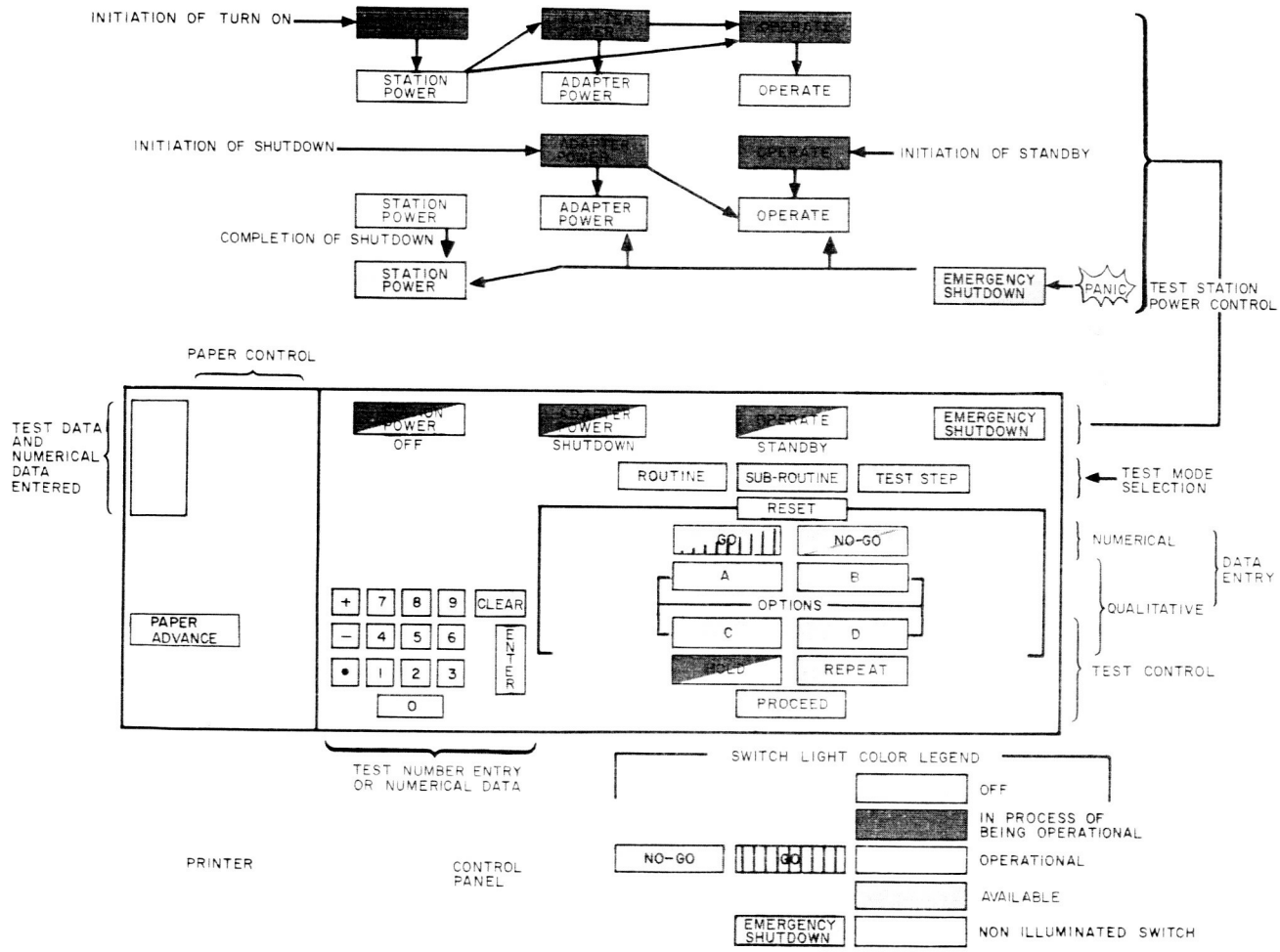

Figure 7. Control Panel

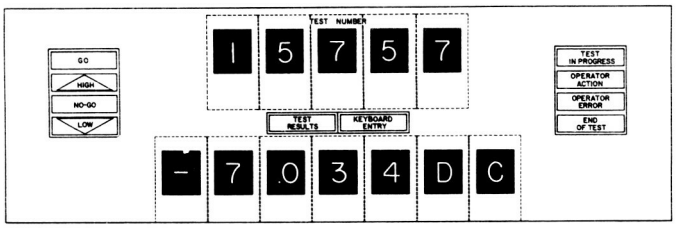

Figure 8. Basic Display Panel

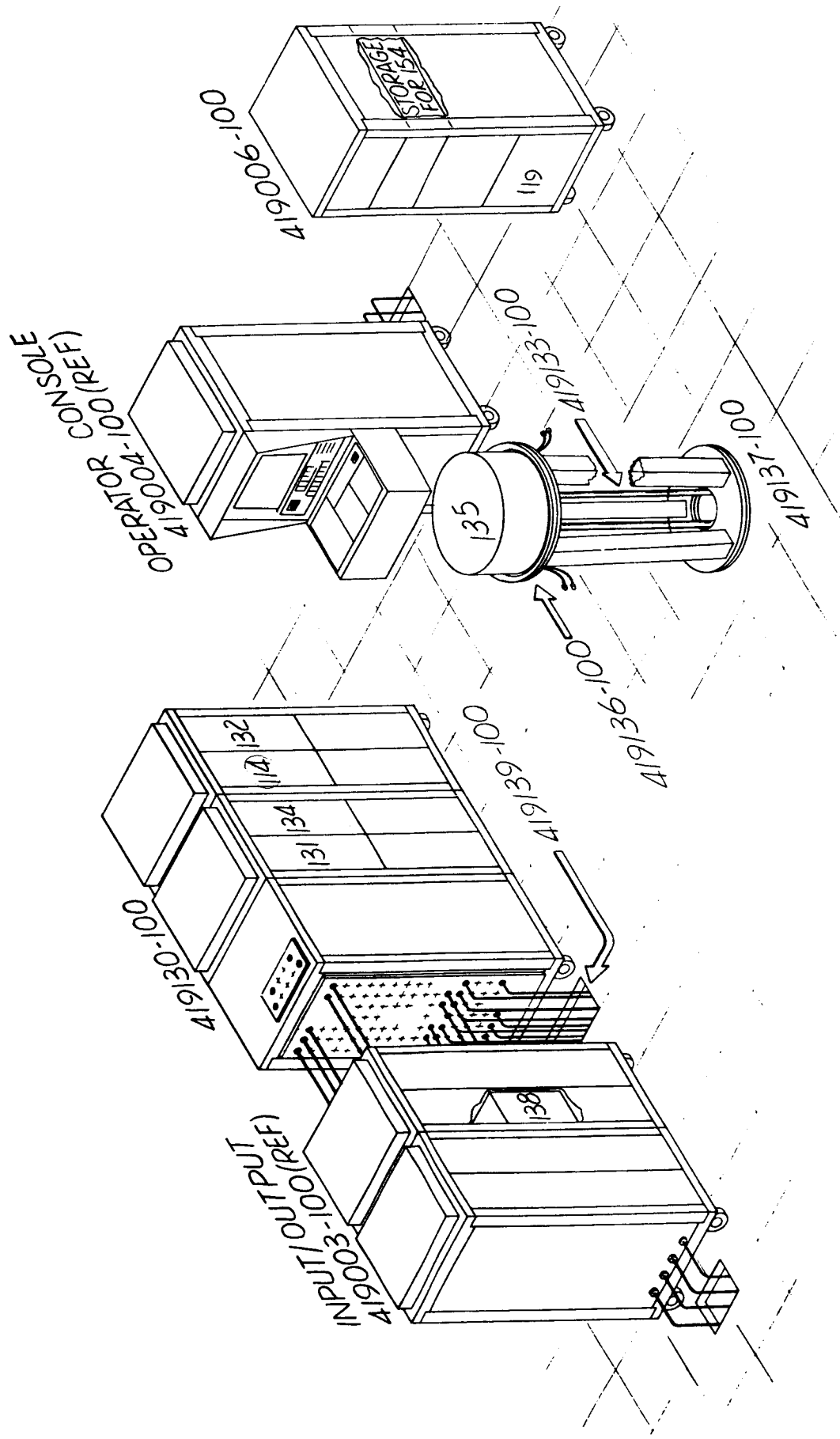

Figure 9. SM-80 Platform Test Station

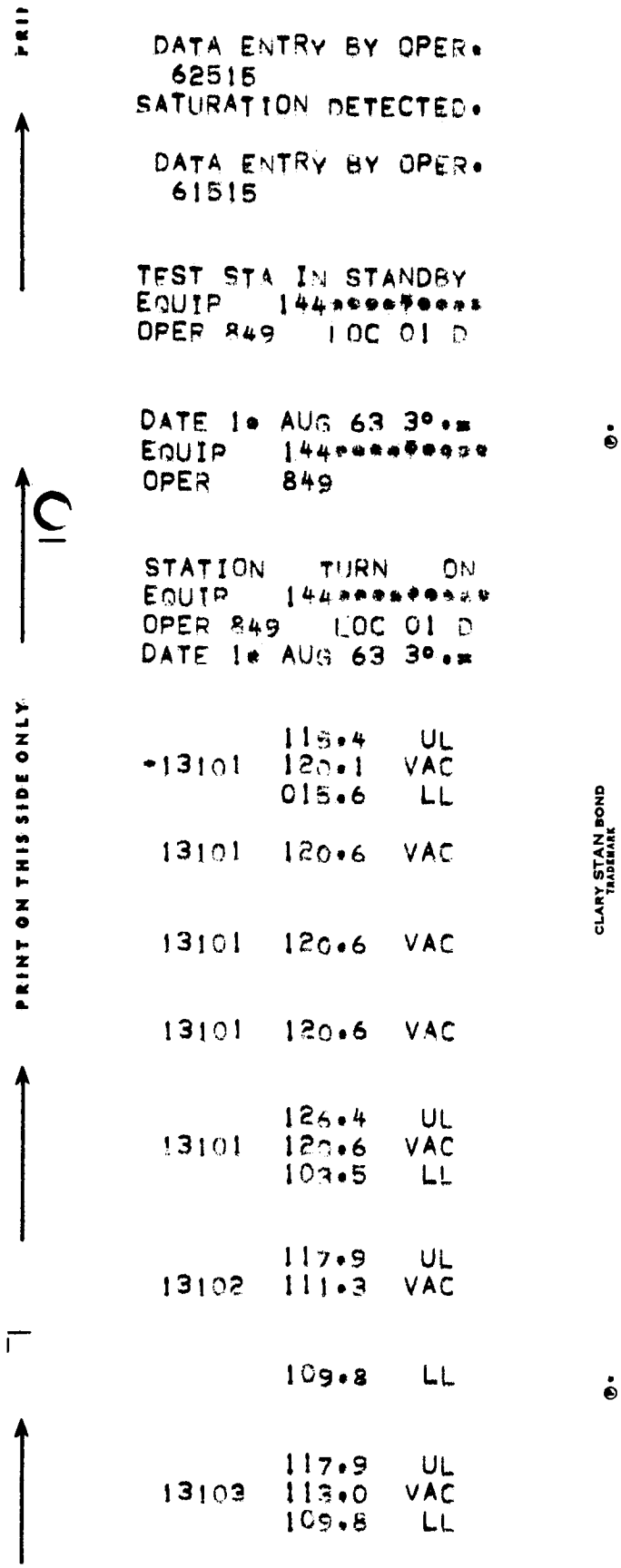

Figure 10. Sample of Printer Output

MAN, MACHINE, AND AUTOMATIC TEST OPERATIONS

G. F. Meister, Jr.

GEORGE F. MEISTER, JR., Douglas Aircraft Company.

Mr. Meister received a BSEE degree (Purdue University) and has done graduate study in computer design and advanced engineering mathematics (U.C.L.A.). He participated in the design of launch and checkout equipment for the operational Thor System until June, 1960; participated in the preliminary and detailed design of launch and checkout equipment for the Saturn S-IV from June, 1960, to February, 1962; acted as Technical Assistant to Supervision for the S-IV launch and checkout system until May, 1962. In May, 1962, he was assigned the system-design responsibility for the S-IVB Automatic Checkout System and participated in the preliminary design of the checkout system and preliminary definition of the programming effort. Present position: Supervisor, S-IVB System Design.

MAN, MACHINE, AND AUTOMATIC TEST OPERATIONS

By: G. F. Meister, Jr.
Douglas Aircraft Company, Inc.
Supervisor, S-IVB Systems Design

The establishment of man/machine relationships within automatic checkout systems is somewhat akin to the weather. Most engineers talk about it, but not too many of these same designers actually get involved, or do anything about it. This is probably brought about by the strange crossbreed of requirements extant for the type of engineer required to solve this problem. For a single individual to be qualified in this area requires a combination of digital systems engineer, operations engineer, programmer, and psychologist, or what is known in the industry as human engineer (implying I'm afraid that there are those of us who are not human). For an individual to be accomplished in each of these fields would require many years of training and experience. Therefore, the usual approach to the problem is to gather together a group of individuals, each experienced in his own area, who try to work together in order to solve the problem. Like all groups, however, the individuals vary in the amount of influence they have over the final group output. The result is that the output generated is roughly equivalent to what the strongest member of the group is capable of, or in more effective cases, what the two strongest members are capable of.

Automation is being attempted for the checkout and static firing of the individual stages of the Saturn vehicle. In addition, it is being attempted for the checkout and launch of the integrated vehicle itself. This attempt is based partly on the success achieved by military missile systems presently operational in the field, and partly on the success achieved by data gathering and parameter predicting systems also operational. Rapid advances in the state of computer design has also contributed to the appeal of automatic checkout systems. However, the communications problem present in the automatic systems now being designed and manufactured is vastly different than most of those previously encountered.

In the typical military missile system the equipment was designed for operating personnel who were considerably less technically qualified than the designers. It was assumed that the operating personnel had little, if any, specialized knowledge of the checkout system or the unit under test. Therefore, the number of displays and readouts provided were generally limited, and certainly not sufficient for any detailed analysis of the test operation. The number of controls and operator options were similarly limited.

The output of typical military systems generally consists of go-no go information, and in some cases, a printed output of the corrective action to be taken. The test procedures themselves are relatively simple and usually include only those operations which could not be implemented automatically. In the design of these systems, the operations engineer was sufficiently experienced to coordinate and, in a large measure, solve the man/machine communication problem. It is probable

that some areas required consultation with programmers, digital designers, human engineers, etc. However, the majority of problems were solvable by reference to the overall operational problem.

In computer systems, per se, the input/output console, typewriter and line printer represent the communications link. In most cases the machines are programmed and operated by the same organization, and in many cases, by the same people. The "user" generally never sees the machine, nor is he aware of the actual operation except to know that his code sheets, or whatever the input form is, turns into the output required, such as reams of line printer outputs, etc. The equipment, therefore, is generally designed by and for programmers. Again certain areas arise that require consultation with other disciplines, but the primary influence is that of the programmer.

The integration of high speed digital computers into checkout and launch systems for space vehicles, along with the additional requirements generated due to the R & D nature of space programs, make both the go-no go and the programmer-oriented type of communication link insufficient for use in these systems. In order to understand the requirements for these new systems, an understanding of the type of personnel involved with the operation of these systems is necessary.

The first stumbling block in the creation of an effective communications link is met in the describing of the operational personnel, for there is no single description that will fit these people. Some are the engineers who are responsible for the design of the various subsystems being tested. Others are test engineers responsible for the successful conducting of the test program. Still others are programmers responsible for the programming and operation of the digital computer system itself. Still others are operational types who do not understand the technical aspects of the operation, but are responsible for meeting required schedules and specifications as part of the overall program plan.

The problem is further complicated by the fact that the operating personnel are generally experienced in the field of stage checkout. In fact, for years through the development of those systems we now take for granted such as Thor, Atlas, Redstone, etc., these same test engineers were the people who had to make hardware do the job regardless of the condition of the stage and checkout equipment when received at the operational site. These people have a justifiable pride in their ability and contributions to the success of these programs. The design engineer, on the other hand, has developed a subsystem in which he has a justifiable pride. If there is something wrong with that subsystem, the designer wants sufficient information to be able to firstly convince himself that it is his subsystem that has failed, and secondly, to tell what is probably wrong and what must be done to correct the fault.

To attack the problem of establishing a communications link which is suitable for use by the many types of operating personnel involved requires an understanding of the elements of such a link. The man/machine communications link contains four basic elements. These are:

1. Those controls exerted through the test program.
2. Those controls exerted during the test operation.

3. That information displayed to allow the operator to make decisions with respect to the test processing.
4. That information displayed to allow the operator to judge the operation of the checkout system and the unit under test.

Control exerted through the test program

Before defining the controls exerted through the test program, it is probably useful to define the test program itself and indicate the steps involved in its generation. The basic computer system is usually a medium-sized, relatively high-speed digital computer. A typical example is the Control Data Corporation 924-A, which is used in the S-IVB Checkout System. With this computer is a group of utility routines to handle such functions as input-output, tape searches, etc., and one or more executive routines. This executive routine normally interprets the test program inputs and causes the proper computer actions to execute the test program. It also monitors the processing of the test program and will generally take care of bookkeeping, processing interrupts, and timing.

The test program itself, then, must be a series of machine words which the executive routine will interpret correctly, and process according to the desires of the test engineer preparing the test program. The test program can best be thought of as a series of calling instructions which represent some required action on the part of the computer, and as a result, on the checkout system. These calling instructions may take many forms. Some of these are forms calling for discrete outputs, analog outputs, time delays, comparisons, measurements and displays. The precise list of calling instructions is a function of the computer and the checkout system.

The problem of man/machine communication is first encountered in the preparation of the test program. It is generally accepted that the person best able to define the test requirements for a subsystem to be tested is the designer of that subsystem. Therefore, the first problem is to establish a means of allowing that designer to express the test requirements of his subsystem in a manner which may be converted into a test program which is usable with the computer-controlled checkout system. The R & D nature of space programs puts an added constraint on the means of getting from designer to test program, in that the time to create and change test programs must be kept short to allow for the development processes that subsystem designs and subsystem test requirements pass through prior to being firmly established.

At present the most promising approach to the generation of test programs which seems to meet most of the requirements of the overall program is the use of a compiler/translater off-line to generate test programs. This compiler/translater accepts as an input either english language or quasi-english language and translates these inputs into the required series of calling instructions in machine language. Quite obviously, considerable gains can be made if the subsystem designer can express his test requirements in english language and engineering units with which he is familiar and have a computer translate these requirements into the proper test program without having to go through a second party. A by-product of this approach is the possibility of standardizing the language used by the design engineer such

that his requirements can be understood not only by the personnel of his own company but also by those of other companies and organizations also working on the same overall program.

The first method of control through the test program is the establishment of the sequence of calling instructions in the test program. Some fairly obvious examples of this is the use of such statements as:

Set Command Relay #55
Measure Fuel Tank Pressure
Execute Digital Data Acquisition Subsystem Test
Apply 5.0 VDC to Telemetry Channel 24 Calibration Input

In the S-IVB program, the test requirements are generated in the form of flow diagrams using the types of statements indicated above. These flow diagrams are then transferred to standard computer coding sheets in a test language that has been defined for the checkout system. This language is very similar to the language used in the flow diagrams, with only minor changes made to simplify the actual compilation operation.

In addition to the action calling instructions noted above, a second type of calling instruction is also available to the test engineer. These are known as control operations. These consist of such operations as "Begin", "Halt", "If", and "Go To". Begin and Halt are fairly self explaining. The "If" statement is essentially a conditional jump statement. It is usually written in the flow diagram in a slightly different form. This form is:

Is the Fuel Tank Pressure Greater than 35 PSIA?

At this point the flow diagram branches to two different paths depending upon the answer to the question. In order to put this statement into a form more compatable to the computer operation itself, the statement is transformed into a conditional jump in the form:

If the Fuel Tank Pressure is Greater than 35 PSIA, Go To XXXX.

XXXX represents the procedure to be followed if the answer to the question is yes. The Go To statement, used here as a part of the conditional jump, can also be used in the test program as an unconditional jump.

Controls Exerted During the Test Operation

One of the most difficult phases of the system design of an automatic checkout system is that phase during which the general operating concepts are conceived and provisions are made to implement these concepts. It's quite obvious that the checkout system must be usable by the operating personnel, or it is of little value. However, as noted before, the operating personnel who use the checkout system in the type of R & D program represented by Saturn stage checkout, are of

varied backgrounds and interests. The operating concepts, then, must in effect provide all things to all people. The test engineer wants a system with which he can get through the test successfully in spite of whatever unforeseen events might take place. The programmer wants a system which allows him to checkout and debug his programs as efficiently as possible. The operations engineer wants a system which he can understand, and which is simple enough that he can have a high level of confidence in its reliable operation. The subsystem designer wants a system that will implement his test requirements, and yet allow him to modify these as experience dictates.

The result of all of these requirements on the operating concepts of the checkout system is, as usual, a compromise. In general, the operating system should be kept simple, if for no other reason than the fact that the computer must process the inputs from the operator and act upon them. An extremely complicated system would put a large burden on the computer itself, and thus reduce its capability to successfully and reliably process the test program. The S-IVB operating system represents a compromise of all of the conflicting requirements put on such a system. In some respects it is more complicated than would be ideal, and in some respects it is not as versatile as it could be. However, it does represent a reasonable approach to the problem, which, with actual experience in the field, should meet the needs of the checkout system and its operating personnel.

The operation of the S-IVB Checkout System is controlled from a Digital Control Panel (See fig. 1). In order to understand the operation of this panel, and how it exerts control over the computer system, it is necessary to ge back to the test program and look at certain elements of it not previously discussed which allow this on-line control. There are two such elements that are a part of the test program. These are the test statement number and the control characters.

The establishment of a test statement numbering scheme is, in itself, a complicated process. The programmers would like the test statement numbers to do all of the machines bookkeeping for it, and yet, the test engineer would like these same numbers to act as a road map to the test program. The test statement number itself has at least three functions. These are:

1. To act as an identifying tag for each test statement.
2. To act as a means of identifying a starting point for a particular operation.
3. To act as a means of indicating to the operator the current point in the test program.

The third function will be discussed in the next section on information displayed to the operator.

The second function, that of identifying a starting point for a particular operation, is relatively straight forward. By inserting a test statement number from the control panel with the keyboard shown, the operator can direct the computer to go to that point in the test and start processing it from there. Some concern must be given to controlling the number of places within a test program that the

operator may start from. This will be discussed shortly under the general subject of control characters.

It is of considerable importance to the programmer that each test statement have some form of identification. Everytime an unconditional or conditional jump is processed within the test program, the location of the new statement must be indicated. In addition, the programmer must have some method of keeping the test statements in the right order and of referring to them when changes must be made to individual or sets of test statements. In most computing systems, a symbolic form of statement identification is used. Before running a program using this form of identification, an assembler must be used to assign discrete computer addresses to the symbolic forms. These assemblers, which are quite common in the computer field, are usually peculiar to each machine, or model of machine. A similar approach has merit for assigning test statement numbers. Instead of an assembler assigning memory locations, however, the same compiler/translator which processes the test language inputs, can also be used to assign test statement numbers. Interestingly enough, it turns out that an assembler must also be used in order to associate discrete memory locations with the test statement numbers.

In addition to the test statement itself, and the number assigned thereto, another character may be used as a part of the complete statement as input to the compiler. This character is referred to as a control character. Four control characters have been defined in the S-IVB system. These are:

1. H - Hold Point - a place in the test program where the system under test is in a quiescent state. It is not expected that the system will stay at this point for any extended period of time.
2. S - Stop Point - a place in the program which meets the requirements of a hold point but has the additional characteristic of being a place where the system may stay for an extended period of time.
3. E - Entry Point - a place in the test program where a test may be entered and executed independently of any part of the test program existing prior to the entry point.
4. N - Do Not Intervene - a statement or series of statements in the test program during which timing is sufficiently critical that it would jeopradize the successful processing of the test program if the computer were allowed to leave the test program in order to do bookkeeping or other non-related operations.

The control characters are added to the test flow diagram after it has been completed. Usually this is done by the programmer or test engineer in conjunction with the subsystem designer who created the original flow diagram. The establishment of control characters may, in some cases, cause revision to the flow diagram. For example, the test engineer may wish to designate an entry point in the test program, but finds that the operation is dependent upon some earlier step in the

program. He must then revise the flow if he is to have the entry point desired. This may, of course, simply involve turning off and back on some function in the system under test.

While the Do Not Intervene inputs control the machine internally, and the Entry Point designations allow entry to start a test, most of the on-line operation makes use of the hold and stop points designated in the test program.

Three means of halting the computer operation are provided on the control panel. These are "Hold", "Stop", and "Emergency Stop" switches. The hold input causes the computer to go on to the next hold point and halt at that point. The stop input causes the computer to go to the next hold point and then back up to the last stop point. The emergency stop causes the computer to halt immediately and jump to a predefined emergency shutdown routine.

Through the use of these inputs the operator can either halt the test momentarily to investigate some event or circumstance prior to continuing (such as a voltage or pressure out of tolerance), or halt the test and reset it to a static condition while minor repairs are made or detailed investigation is carried out, or to get the unit under test into a safe condition and the system shut down to avoid what might become a serious condition. Once the test is halted, there must be, obviously, a means of starting it again. Two inputs are provided to do this. These are the "Resume" and "Clear" switches. The resume input causes the computer to start processing the test program from the point at which it has halted. The clear input causes the computer to reset the system to the state it was in prior to the beginning of the test program, and to process the next test designated by the operator.

It should be noted that both the stop and clear inputs imply a reset routine. It becomes increasingly clear with experience that a reset routine is not necessarily the test program in reverse, and that the reset routine is a constantly varying thing depending upon the status of the system and the current point in the test program. At present, the handling of resets in the S-IVB system is considerably more awkward than is desirable. It is hoped with further investigation and experience that a clean, and hopefully simple method can be established to generate these routines during the test operation.

The controls discussed so far represent a minimum requirement in order to allow the control of the test operation desired by the test engineer. However, the programmers involved do not have, with only these controls, the versatility of operation necessary to properly and efficiently checkout their programs. The programmer requires some control over the mode of operation of the computer with respect to the manner in which the test program is processed.

Four modes of operation can be defined within the structure of the test program. These are:

1. Processing of the test program as an entity without halt unless a fault is encountered or the operator intervenes.

2. Processing of the test program in relatively large increments with lengthy halts between increments.
3. Processing of the test program in relatively short increments with shorter halts between increments.
4. Processing of the test program one test statement at a time.

The first mode requires no implementation, since this is the normal mode of operation. The second mode is readily recognizable as, in effect, processing the test program from stop point to stop point. Therefore, an "Enable Conditional Stops" switch is incorporated on the control panel. This input causes the computer to treat each stop point as a halt instruction. The "Resume" switch is used to continue on to the next stop point.

The third mode can likewise be related to processing the test program from hold point to hold point. Therefore, an "Enable Conditional Holds" switch is incorporated on the control panel. This input will cause the computer to treat each hold and stop point as a halt instruction. Again the "Resume" switch causes the computer to continue. The fourth mode is not incorporated into the S-IVB system directly, but will be discussed later.

Although the above capabilities were incorporated into the system primarily with the programmer in mind, it can be seen that they also represent powerful tools to the test engineer during the actual test operation. Through the use of these switches the operator has the capability of slowing down the operation and in essence going through the test step by step. This form of operation allows the personnel connected with the test to keep current with the test operation and actually verify the operation as it is carried out.

One further capability seemed necessary during the evolution of the S-IVB operating system. It is assumed that none of the test programs will be perfect when they are first used. Nor will all of the possible contingencies have been considered and preprogrammed. Therefore, it is desirable to have the capability of interrupting a test program and jump to some other part of another program in order to accomplish some task that should have been, but was not, incorporated in the original test program. It is equally desirable to be able to return to the original test program at the point from which it was left. Therefore, a "Store Program Point" switch is incorporated on the control panel. This input causes the computer to store its current position in the test program and standby for a new starting point to be input by the operator. All of the other control previously described is now applicable to the new program being processed. By turning off this input, the computer is caused to return to the original test program at the point where the input was turned on.

Although this capability was originally incorporated to allow the establishment of a linkage between two test programs, several side benefits are also accrued. Since there is no restriction as to what test program may be jumped to in this mode, there is also no restriction that it necessarily be a test program per se. Therefore, two special routines are presently defined which may also be entered

in this mode. One of these establishes typewriter communication between the operator and the machine, which allows a limited on-line modification of the test sequence or the generation of short routines to be executed on-line. The second causes the computer to go into an operating mode such that the test program is processed one test statement at a time dependent upon the operation of the "Resume" switch as the triggering factor. Therefore, even though, as noted before, the single test statement processing mode is not incorporated on the control panel directly, it is implemented in the system through this special capability. Obviously, other special routines can be written as required by future circumstances.

Information Displayed to Allow the Operator to Make Decisions

To a large extent, the information presented to the test operator on which he must base on the spot decisions is somewhat fixed by the controls he has available. For example, he must have an indication of the cause of any halts in the test operation. Therefore, indicators are provided showing the existence of a hold, stop, or emergency stop and whether that halt was generated by the computer or the operator. Also indicators are necessary to acknowledge operator inputs such as conditional holds or stops enabled and program point stored.

Secondly, the operator must have the benefit of the computer's preliminary analysis of any faults that appear in the system. This information can be presented on a CRT display (which will be discussed in more detail in the next section), on the typewriter or line printer. Regardless of where it is displayed, all of the information available to the computer regarding the fault should be presented to the operator. The operator must then decide whether to continue on with the test, or to clear that test and process another. To specify that a test must be "scrubbed" whenever a fault is found is not reasonable, particularly in the early phases of factory checkout. Therefore, the operator must have the capability of testing around a fault as much as possible to find other faults before shutting down the system. Even in the case of "scrubbing" the test program being processed, the operator must decide which other, if any, test programs may be processed under the circumstances.

Information Displayed to Allow the Operator to Judge the Operation

This type of information covers that data displayed to the operating personnel both during and after the operation. A considerable amount of time can be saved in the overall test operation if sufficient information can be made available to the test operators during the processing of the test such that tests may be "bought-off" as soon after their completion as possible. It is highly desirable that the system configuration used during a test not be disturbed until the test is bought off. This is based upon the consideration that if a fault is found during post test analysis that requires rerunning the test, it is desirable that the system not have changed configuration between the two runnings of the same test program. However, it has been true for many years that more time is consumed setting up and tearing down for tests than is consumed in the actual test operation. The advent of automatic checkout systems does nothing but accent that fact. Therefore, the

total time required at any given site to accomplish a testing program becomes primarily a consideration of set up time for the test operations. Reducing the interval between tests by timely displays to the operating personnel can mean a significant savings in time and money for an overall program.

In addition, the operating personnel can contribute to the test operation directly in proportion to their capability of understanding what is occuring during the processing of the test program. This capability is directly related to the amount and quality of the information presented by the automatic system. In the same vein, the automatic checkout system inevitably contains certain manual controls which allow the operating personnel to take over control of the system and put it in a safe condition should the computer or automatic system fail. In order to be able to perform this backup function intelligently, the operating personnel must be aware of what is taking place in the test program and what the state of the unit under test and the checkout system is at any time in the test operation. This is, in fact, a pretty large order for any display system.

The actual hardware used to provide the required information to the operating personnel will vary from system to system. However, it generally falls into four categories. These are:

1. Standard computer peripheral equipment such as typewriters, line printers, etc.
2. Standard recording devices such as strip charts, event recorders, etc.
3. Standard indicators such as meters, lights, etc.
4. Special display devices such as CRT displays.

The typewriter and line printer seem like logical choices for displaying data from the computer. However, each has a serious disadvantage. The typewriter is too slow to output any amount of meaningful data in a short period of time, and is certainly not fast enough to keep the operating personnel abreast of the test program operation. The line printer is much faster, but is difficult to read directly during an operation. In addition, both of these devices require a considerable amount of computer time to operate. The typewriter is useful for small amounts of information, and the line printer is specially useful for post test outputs. However, neither meets the requirements for on-line information display.

Standard recording devices such as strip charts and event recorders are useful to provide hard copy for post test analysis and a certain amount of on-line monitoring. However, these devices are best used in parallel with the computer system. Attempts to drive these devices leads to considerable requirements in terms of driving hardware, and in the case of analog values, prohibitive computer time requirements to drive the recording devices.

Standard indicators such as meters and lights are useful for monitoring certain critical functions. Again, these devices are best used in parallel with the computer system. In general, the use of these devices is in effect defined by the establishment of those manual controls necessary to backup the automatic system.

Because of the above considerations, a considerable amount of attention has been given to the incorporation of CRT-type displays into the Saturn automatic checkout systems. Many different types of CRT displays have been, or are being, evaluated for the Saturn program. No effort will be made herein to describe any particular display system. However, certain ground rules should prevail for any such display system incorporated as part of an automatic checkout system. These ground rules are:

1. The display system should provide real time information to the operator in a form that may be readily understood without reference to supporting documentation during the operation. This implies that the display should have an output in engineering units with sufficient identification of parameters such that the information is recognizable to operating personnel familiar with the system under test.
2. The display system should have sufficient flexibility to allow changes to the number and arrangement of parameters displayed. Since one of the attributes of an automatic system is the capability of modifying the test program through changes to the software, and thus reduce the reaction time of the checkout system to changes in the unit under test, this same short reaction time should be achievable with the display system.
3. The display system should be such that it requires a minimum amount of computer time to process and update the information displayed. This implies a minimizing of the total computer requirements of the display system. These requirements may include such things as data processing, tape searches, computer input-output, etc.

Two generations of CRT display systems presently exist. The first uses the CRT as an electronic line printer. Many models of this generation system exist in use today. This technique combines the readability of the typewriter with the speed of the line printer.

Generally the line printing CRT display is used in conjunction with a program that essentially dumps a designated portion of memory into the CRT display system. It is capable of presenting real time parameter values by inserting these numbers into predesignated memory locations adjacent to other locations having parameter identification information prestored. While this approach does, essentially, meet the first two requirements for a display system (parameters are displayed in engineering units and the block of memory being dumped can be modified under program control), it falls woefully short of meeting the third criteria. It may be conservatively estimated that four words of identifying data is required for each word of meaningful information (in more complicated systems this ratio may go to ten to one or higher), the computer must process, store, and output four or more times as much data as would be necessary under more ideal conditions.

The second generation of CRT displays include some internal memory to alleviate the computer load. Most models of this generation are still in the development stage, although several are now in production. This internal memory varies with models from high speed core memory to slides or film strips. In this type of

display the information is broken down into two distinct types, static and dynamic information. The first, static information, is made up of parameter identification and any other supporting information such as limits, etc., that is meaningful. The second, dynamic information, is the actual parameter values measured in real time by the checkout system. These two types of information are then married within the display unit either within the memory, or optically, or electronically in the video portion of the display system.

In those display systems using core memory, the computer need only output the parameter values as long as the number of parameters being displayed in any test sequence does not exceed the memory capability supplied for static information. If the memory capability is exceeded, the computer must then also output that information as in the case of the CRT line printer. However, this static information need only be transmitted once, as compared to the first generation display system where it must be transmitted each time the parameter values are updated.

In those displays where slides or film strips are used, the static data is contained on the film and does not require any computer time to generate or transmit. This technique provides a large amount of internal storage at a very low cost and in a form compatible with video displays. This technique has the added advantage that the static information may be changed off line without requiring digital equipment of any kind.

In systems the size of those being developed for stage checkout on the Saturn program, a single display system seems to be adequate, although experience may show that two or even three such displays, each independent of the other, are required. As long as the third criteria is met by these display systems, that is that the computer requirements to process the display systems is kept to a minimum, it also is evident that a computer of the capability commensurate with that being used in the S-IVB system can handle both the display and test program processing simultaneously.

However, when the launch of the integrated vehicle is considered, or when future programs involving even bigger and more complicated systems are considered, it becomes obvious that multiple display systems are required due to the large increase in the amount of information required in a given time. It also appears that these displays will be of sufficient number that they must either operate essentially independently of the computer controlling the test operation, or that a second computer will be required to service the display systems. For the display system to operate essentially independently of the computer will require yet another generation of display systems to be developed. Considering the cost and time involved in the development of the second generation, it is more likely that a second computer servicing a group of the presently being developed second generation display systems will be incorporated in these larger systems.

The foregoing discussion of the establishment of a satisfactory man/machine relationship in automatic checkout systems may be summarized quite briefly. It must be realized that the establishment of the required communications between the

operational personnel and the machine is one of the largest single tasks before the system designers of automatic checkout systems. The requirements imposed upon the system are far reaching and cannot be established too early in the system design. The definition of the process for generating test programs, the test language, the test statement numbering scheme, control characters, on-line controls, on-line indications, and display systems affects every facet of the hardward and software design. The computer is built into the system to help the man do a job. The man must be able to communicate with it and control its operation. Until such time as we are prepared to turn the entire operation over to computers (a situation which may or may not ever occur) it can be no other way.

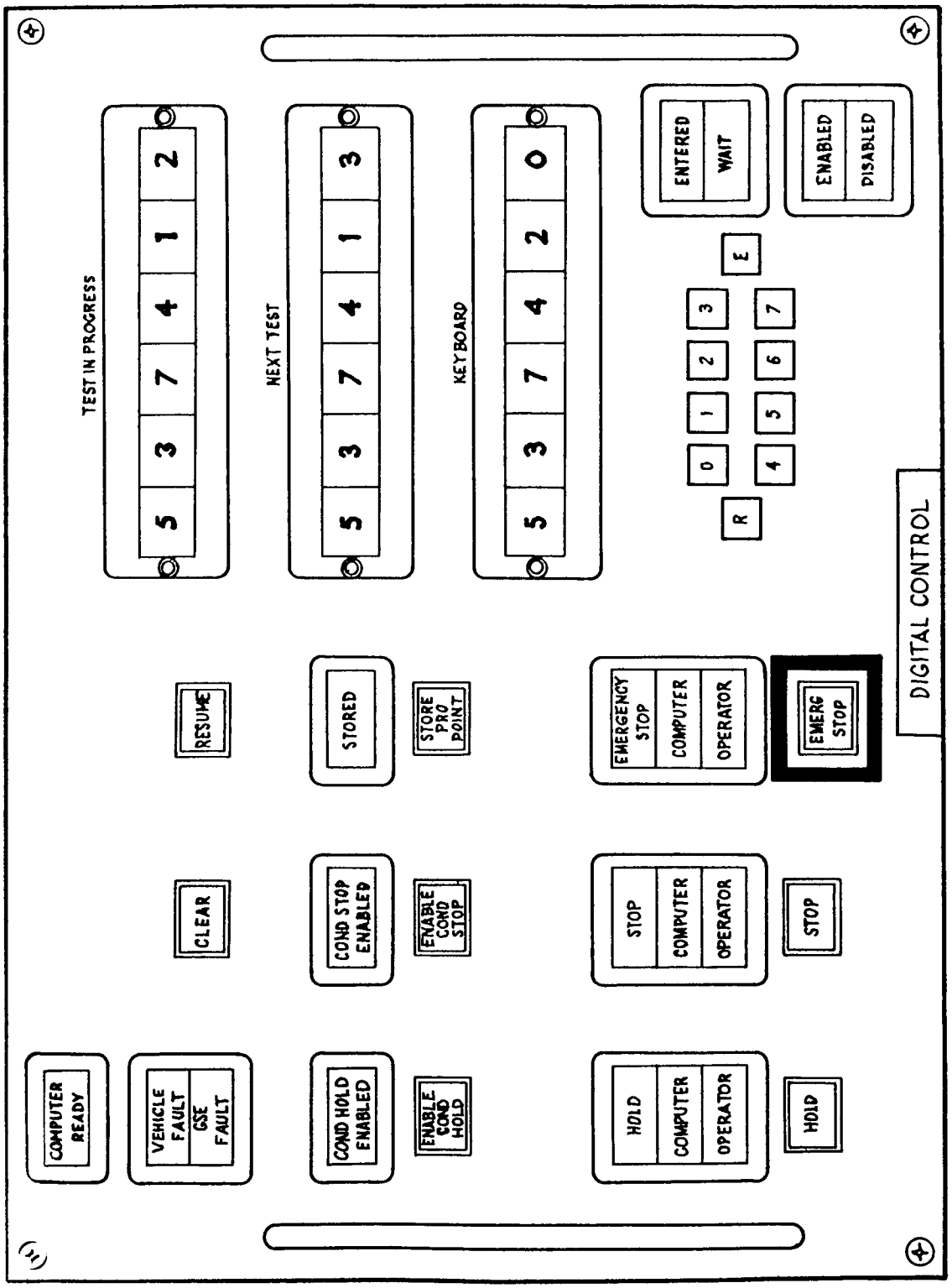

Figure 1. Digital Control Panel

AN APPLICATION OF ARTIFICIAL INTELLIGENCE TO SYSTEM TESTING

John C. O'Brien

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AN APPLICATION OF ARTIFICIAL INTELLIGENCE TO SYSTEM TESTING

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The purpose of testing is the extraction of information on the condition of the system tested. This information must be recognized and understood in the context of the system design - it must make sense, in terms of system performance. The role of intelligence is to provide interpretation or "mapping" from the randomly coordinated test data to the analyst's concept of the system function.

Mechanizing or artifacting a portion of this task of intelligence requires a rationale of intelligent operation. A common basis for both system performance and the intelligent "brain" must be included in this rationale. One inescapable common basis is the existence of both of these in the physical world. The energy laws and the principles of information generation and transfer, apply to both. Also, translation of system performance state information, from the data to the diagnosis, ordinarily is made through these or other language media.

The synergomorphic language medium proposed here is called SPAN, and is novel to "lumped" systems, but has been applied to distributed states for many years. It consists of the algebra of the laws of energy physics, as weighted by "negentropy" figures of merit. The physical laws are the generalized forms of engineering principles, and can be reduced to the latter in every case. "Negentropy" is a term from information theory applied to the quality or "ordered" state of energy, and embraces such parameters of performance quality as reliability, effectiveness, efficiency, kill probability, information (carried by energy), availability, and thermo-dynamic entropy.

Since both energy and information are common to all physical phenomena, intelligent or otherwise, the use of both together provides considerable power for analyzing and combining data on system performance.

So far we have covered nothing unusual. Now, however, we break new ground by joining energy and information at a theoretical level. The first result of this "marriage" is to greatly simplify information theory as it applies to "bound" information. The second result is to find that they have been married before, but the marriage has not been generally recognized as such.

The third result is what might be called an "offspring" of the marriage -- a unified system theory, capable of explaining complex system behavior in simple terms. A natural consequence of this simplification is the ability to build models or simulations, based on the combined theories.

The theoretical combination occurs in the many questions for energy flow. The heat diffusion equation is the simplest example:

$$\nabla^2 E = -K \frac{\partial E}{\partial t} .$$

This is practically an "Ohm's Law" for energy, in which $\nabla^2 E$ is the energy concentration or "lumpiness", K is the flow path impedance, and $\frac{\partial E}{\partial t}$ is the flow rate. $\frac{\partial E}{\partial t}$ is also the availability, by definition, of energy at a point. This can be equated to entropy, etc., in terms of the probability of the energy reaching that point, in which form it becomes "information".

Performance, however, is more than just the energy described above. It implies work in a particular functional pattern, to do a specified job. Hence a performance analysis requires taking the functional pattern into account as well as the amount of raw energy. This can be done to a useful degree by measuring the information content of the pattern, in each dimension of interest. Although this procedure neglects the peculiar non-permutative unique signature of a special pattern, as a figure of merit it is still extremely useful. It resembles the "calorie" in food chemistry which is very valuable for balancing diets, although the calorie does not tell us the nature of the rated foods.

The model proposed and experimentally tested for system diagnosis uses this "calorie". It is called the "energy-bit" or performance availability unit (PAU). When a system is described in these units, it is found that they flow through the system just as electric charges flow in an electric circuit. Electric circuits have been used for this purpose to constitute the image forming model or "brain" of the intelligent machine.

The analysis of system test behavior can then be made by comparing levels of electrical quantities in the "brain" (called SPAN, for System Performance ANalyzer), with corresponding levels of energy information. From test points in the real system not only can failures or degradation be recognized by obvious differences between the system and the model "brain", at the test points, but the causes of the degradation can also be deduced by relying on the principle that the logics of the system and the "brain" are identical. Usually, simple trial circuit analysis reasoning will immediately explain the failure mechanism. If not, a manipulation of the element values of the SPAN model to

match more closely the actual condition in the real system will often disclose the true nature of the trouble. Of course, the success of this process depends somewhat on the complexity of the real system functions lying between two adjacent test points. In most cases, however, the power of SPAN's combined energy-information flow logic is sufficiently greater than conventional digital program logic, that the improvement in diagnostic capability is quite pronounced.

This type of artificial intelligence has been applied to a number of complex systems to diagnose both static and dynamic performance problems. Although these have not been real time analyses there appears to be no great design difficulty involved in connecting a "SPAN" model "brain" to an operating equipment system as part of, or in conjunction with, monitoring and test and checkout equipment. The "SPAN" modelling has not yet been made self-adaptive, so that the circuit configuration must be pre-programmed to match the particular system in question.

The components used in a SPAN model consist mainly of resistors, operational amplifiers, comparators, capacitors, and readout devices. In a typical SPAN model "brain" used to analyze a large-scale digitized surveillance command and control system, 20 potentiometers, 40 comparators, and 12 operational amplifiers were used. Capacitors are used to simulate time degradation of performance in reliability studies.

The most striking result of the use of a "SPAN" model "brain" has been the frequent recurrence of the typical analyst's reaction: "Of course! why didn't I see that before", and the intuitively satisfying character of the conclusions. Expert knowledge of network theory is a great advantage in this kind of analysis since it facilitates translation directly from circuit conditions to explanations of system behavior. The requirement for energy-information impedance matching for optimized performance is an example of transfer of a useful algorithm from the model domain to that of the subject system.

A typical system with associated test and checkout complement is shown in Figure 1. The appropriate SPAN model diagnostic "brain" is shown in Figure 2. The combination of the two and the system status readout points are represented in Figure 3. This arrangement as shown depends on human operation for best results. Automation of the fault isolation, diagnosis and readout can be accomplished to a degree by a multi-variable feedback loop. The loop will depend on the differences between corresponding points of system and model for actuation of the adjustments matching the "brain" to the actual condition of the faulty system. This model requires conversion between the checkout system readout and the SPAN brain, from conventional parameters into energy-bits, usually as a digitized word which is translated by a digital-analog converter into voltage.

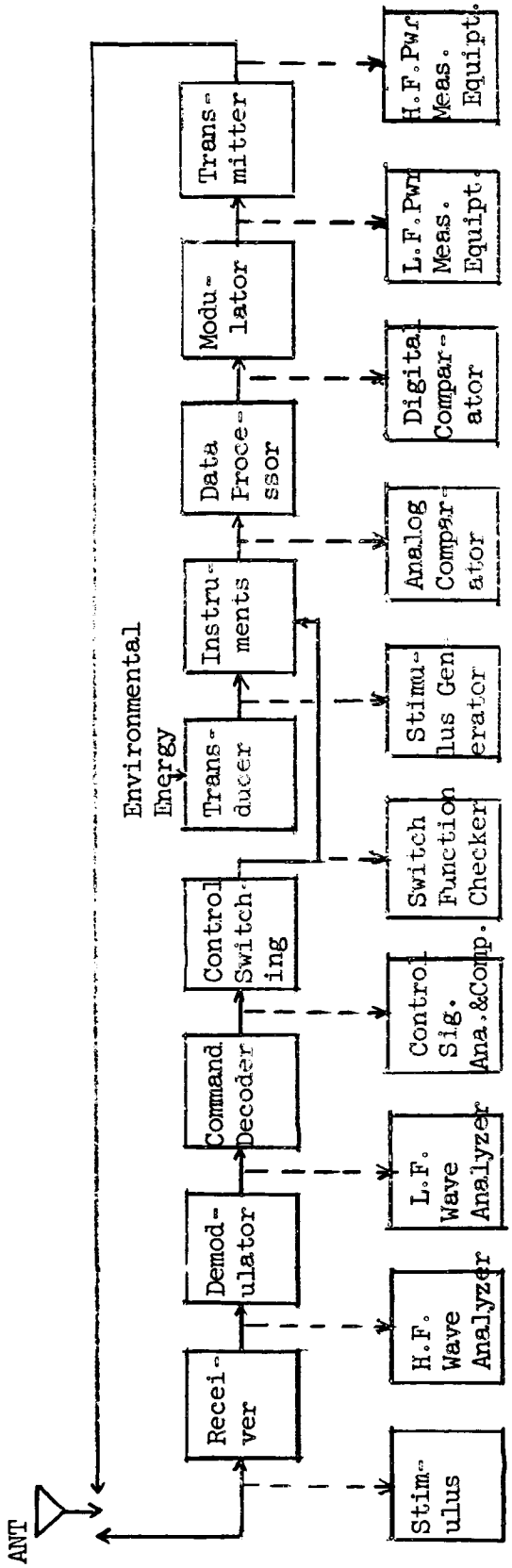

Figure 1. Typical Surveyor Information Channel

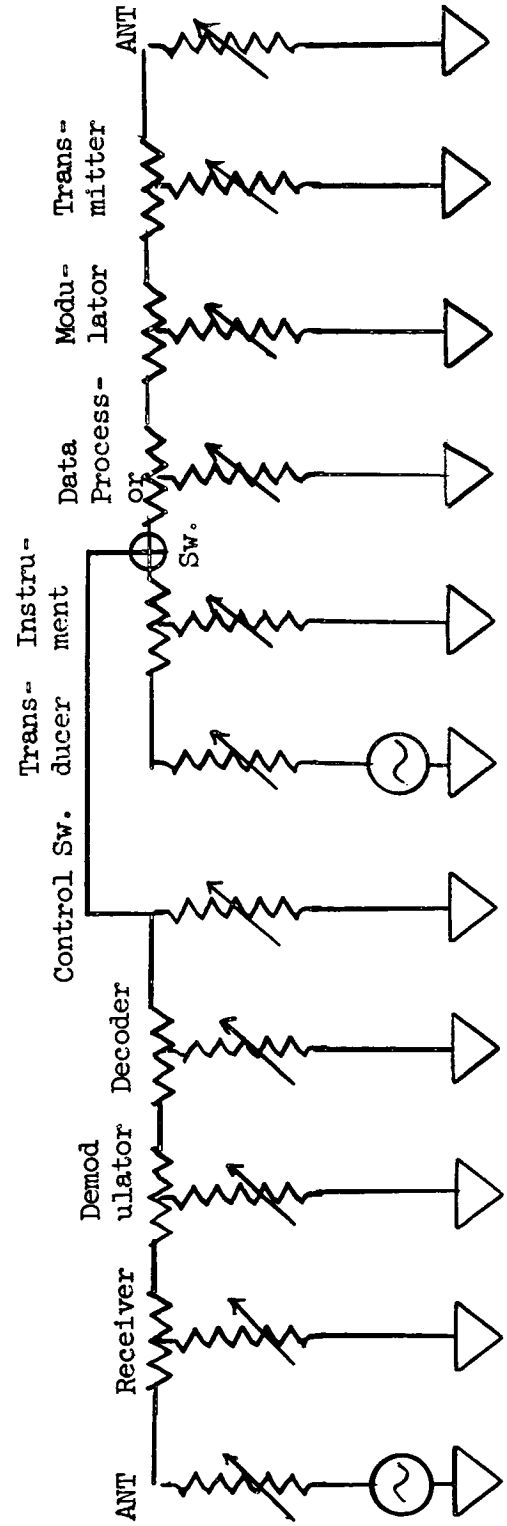

Figure 2. Span Model Diagnostic Brain For Surveyor

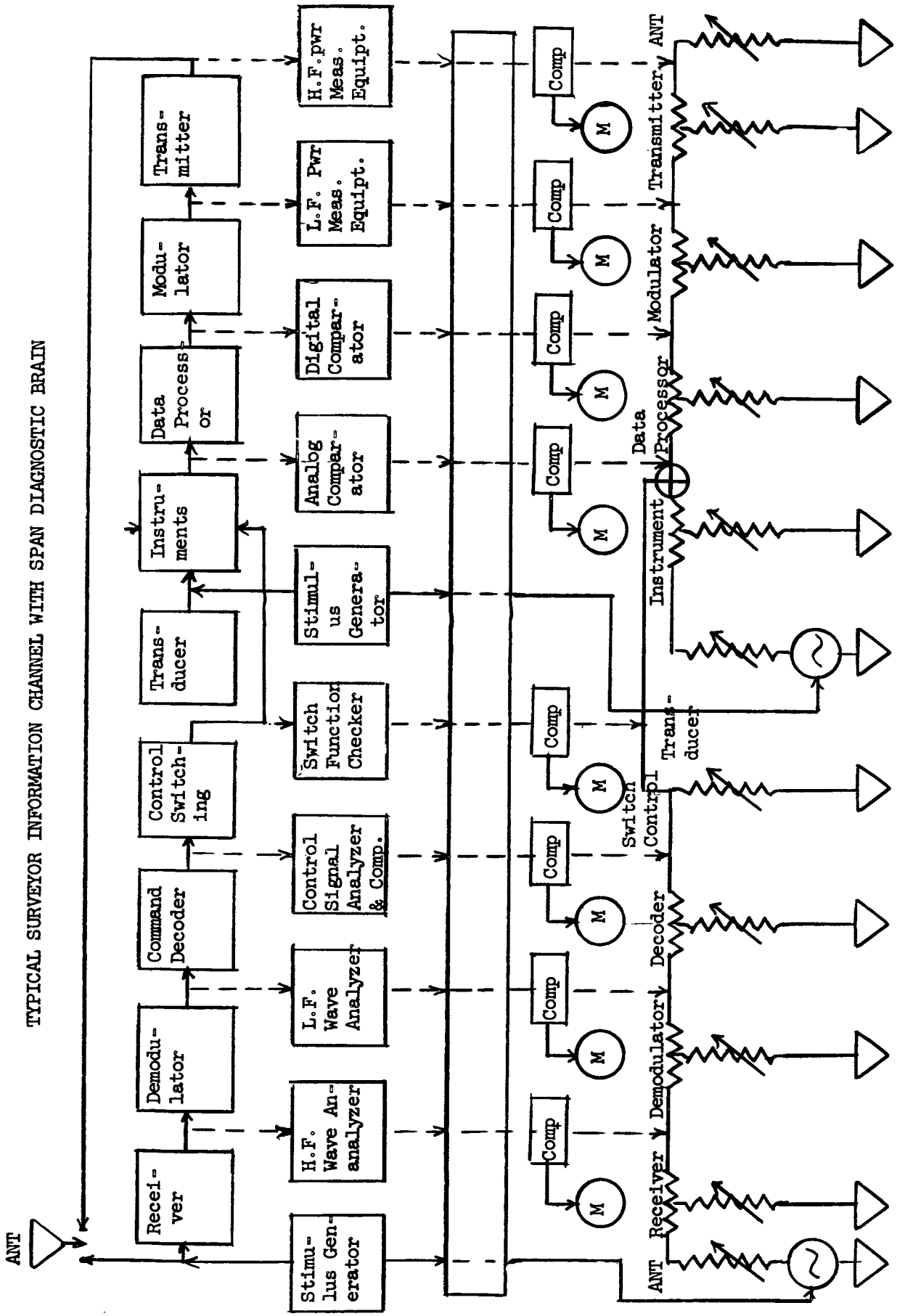

Figure 3. Typical Surveyor Information Channel With Span Diagnostic Brain

A NEW DIGITAL-TO-VOICE CONVERSION DEVICE

Douglas S. Durie and Elmer F. Clune

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A NEW DIGITAL-TO-VOICE CONVERSION DEVICE

(ORATE, Ordered Random Access Talking Equipment)

by
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Elmer F. Clune
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Buffalo, New York

INTRODUCTION

For the past year and a half Bell Aerosystems Company has had under study and development a digital-to-voice conversion system under contract to the Systems Research and Development Service of the Federal Aviation Agency. This converter forms part of system designed to automate a broadcast task now accomplished manually. During the study, the general needs for digital-to-voice conversion were examined to determine which technique would be most fruitful from the stand point of widest application, cost, reliability and quality of voice reproduction. This paper reports on the basic problem, the considerations leading to the selected design approach, the detailed design and possible applications of this device to automatic checkout.

BASIC PROBLEM

As use of electronic data processing equipment is added to every facet of military and industrial operations the need for improved communications between machine and man increases. As such use of data processing and data transmission systems increases there are numerous instances where VOICE readout or communications to the human operator from computer controlled or computer assisted systems is highly desirable. Since the great majority of systems monitoring or systems checkout is accomplished with digital systems any new voice readout device should be controllable by a simply formatted digital command code to produce highly intelligible, reasonably pleasing voice.

There are three principal approaches to the production of intelligent speech. These are:

1. Synthetic reproduction from tones.
2. Synthetic reproduction by control of an analog of the human voice reproduction system.
3. Vocabulary look up.

The latter of these methods was principally investigated to enable staying within the limits of todays developed technology and to meet the economic aspects of wide and immediate application.

DESIGN CONSIDERATIONS

In accomplishing the design of a voice machine, employing the "look-up" technique of speech composition, the following items must be given due consideration:

a) Reliability
b) Maintainability
c) Quality of voice reproduction
d) Ability to handle intermix of words and phrases
e) Digital control
f) Cost and complexity
g) Modular design to permit expansion
h) Ease of changing vocabulary

To ensure reliability, maintainability and quality of voice reproduction only proven state-of-the-art techniques were considered where possible. Use of proven techniques for the machine to be described, has resulted in a low cost and relatively simple design.

To enhance intelligibility and naturalness of the voice reproduction, it was concluded early in the study, that the machine must have storage for, and be able to play back, with essentially no delay, various length vocabulary items. It was found that when all the speech produced is made up of individually stored and retreived words the results are not adequate from a listeners fatigue or acceptance standpoint. The playback of an intermix of prestored words and phrases rather than all singly recorded words can produce acceptable sounding speech.

For a machine to have wide application potential it is necessary that its basic design be modular to allow expansion to suit the need. The machine designed has a basic storage of nearly one thousand words and is expandable to almost any storage capacity.

Although a vocabulary for a given application is not likely to change often, it is desirable to be able to change the stored vocabulary with ease. Also it is desirable to be able to return to a previous vocabulary or to change to a variety of vocabularies. The storage medium must be low cost to permit variety and it must be relatively inexpensive and simple to produce a stored vocabulary. The technique of recording on film strips provides a very versatile and inexpensive vocabulary storage.

As has been stated, the basic control of the machine must be by digital command to be most compatible with the digital environment that we find in modern operations, both military and commercial. To enhance reliability it is further of advantage to make the basic accessing in vocabulary readout digital in nature. This was accomplished thereby eliminating the necessity of converting from digital to analog quantities as is necessary in galvanometer light

directing readout schemes and other similar readout arrangements. This digital accessing is positive and is not fraught with drift, need for daily adjustments and the like, often required in analog schemes.

DESIGN DESCRIPTION

GENERAL: A pictorial representation of the selected implementation is shown in Figure 1. Four film strips each carrying 32 variable width sound tracks are held about a transparent transport cylinder. These four strips store a total of 537 seconds of variable length vocabulary items. For readout of these sound tracks seven reading heads and associated optical light collection systems are spaced equidistantly about and inside the transport cylinder as shown. One of the heads is shown as an exploded view pictorial. Figure 2 shows a photograph of the developmental model in operating status. Figure 3 shows a photograph with one reading head swung back on its hinge mounting to show detail of the reading head. The four film strips can also be seen in position via the reading head opening in the main support frame.

OPERATION: Seven heads are provided to permit immediate accessing of any vocabulary item of incremental time lengths of 0.6, 1.2, 1.8, 2.4, 3.0, 3.6 and 4.2 seconds. By using a technique of "fitting" all vocabulary items into multiple increments of 0.6 seconds immediate accessing is possible. Figure 4 shows a typical arrangement for vocabulary placement on the total of 128 tracks. Upon completion of readout of a previously selected vocabulary item, instant readout of a next selected item is accomplished by selection of the proper reading head, that head falling directly over the start of the next selected vocabulary item.

After the proper head is selected, readout of the vocabulary item is accomplished by electromechanical "switching" of light to a reading slit over

the appropriate track. This is accomplished by position control of seven matrix blades each with a particular binary related hole pattern. These matrix blades are placed as shown, between a light source and the reading slit plate. Each blade has two positions of extreme travel along its longitudinal axis, one extreme position representing binary "zero" and the other extreme position representing binary "one". The hole patterns on the seven blades are such that for any binary combination of extreme blade positioning (either by solenoid motor action or spring return) one and only one continuous light path is provided from the light source to any reading slit. Seven blades thus provide for a track selection capability of 2^7 or 128. The reading slit plate is placed in very close proximity to the film strips. The matrix illumination of the reading slit over a particular track causes a narrow beam of light to be cast onto the moving sound track. As the moving variable width sound track modulates this beam of light, the light is collected and imaged on the cathode of a photomultiplier tube to render the modulation of this light into electrical audio signals.

This techinque of light switching provides a very simple and powerful accessing means that is digital in nature and simple in control. Each head contains seven drive solenoids with spring return to provide 128 reading points. The total compliment of seven heads provides a total of 896 reading points. Solenoids representing the same significance of binary digit can be driven by a common drive amplifier. Thus only seven solenoid drive amplifiers are required. To allow such a common drive amplifier for each of seven binary digit blade control, a latching switch is required for the commons of all solenoids for each head. Figure 4 shows this drive control along with a simplified block diagram of the complete control circuitry.

For complete command control, information must be received by the system as to the x and y storage location of a vocabulary item and its playing time. If no restrictions are placed on the location of vocabulary items on the storage film strips, a thirteen bit command structure is required. Seven bits are required to indicate the track location. Three bits are required to define to which of seven starting locations a particular vocabulary item is assigned and three bits are required to indicate a playing time of from one to seven time increments in length.

To describe general logical control refer again to Figure 4. An optical synchronizing pickoff is provided to synchronize the start of all vocabulary items with the control logic. A pickoff disc is attached to the drive of the transport cylinder and is driven at the same speed. This disc has a pattern of holes as shown, one hole each 1/7 of a revolution. Note one hole is on a different radius. Two light pickoffs working with appropriate illumination lamps provide synchronizing signals to the control logic. As shown, one pickoff provides a once around synchronizing signal to reset the "Position Increment Counter", the other pickoff provides position increment pulses to the same counter. The count in this counter then represents the position of the transport cylinder.

When no vocabulary item is being read out, the latch flip-flops are all in the reset state and no heads are activated. The "Next Command" gate is open and the increment pulses are sent to the control computer each 0.6 second requesting a next command. When the control computer receives this request pulse, and it has a command ready, it transmitts this command on 13 lines plus a signal, slightly delayed, on a fourteenth line to actuate the reading of this

command signal. Seven bits of the 14 line command are used to control the blade position directly as shown. Bits 8, 9 and 10 are used as information to select the proper head. Since this is a function of the vocabulary item position on the film storage as well as the position of the transport cylinder relative to a reference position, a matrix is required to read the position counter and the three position command bits. Bits 11, 12 and 13 are used as vocabulary item length information. An appropriate matrix is used to preset a three bit counter used to time the number of time increments a reading head shall remain latched. When this counter reaches full count it resets all head latch flip-flops and sets the "Command Gate Flip-Flop" to open the "Next Command Gate" thus sending out a request pulse for a next command.

Inter-vocabulary item delay due to control logic operation are of course negligible. A total of 50 milliseconds of inter-vocabulary item delay is required to allow for switching of the matrix blades plus a time allowance for spatial distribution of the reading slits.

EXPANSION CAPABILITY: The developmental model is a basic module having a storage capacity of 896 short words or equivalent phrases. An additional storage cylinder can be added to the basic module attached as an integral part of the total framework. Only an additional storage flip-flop and other minor logic changes are required in the control logic to accommodate the extra cylinder. Various synchronous drive arrangements have been investigated to indicate feasibility of unlimited expansion of this type of random access vocabulary storage.

APPLICATION TO AUTOMATIC CHECKOUT

Man has always been and will continue to be an essential part of any checkout system. Even with the most advanced electronic data processing equipment, man

must be there to check its proper functioning, to set up proper programs, etc. As electronic systems become more sophisticated and complex, however, checkout procedures become correspondingly more complex. Chances for human error become greater through omission of instructions and possible lack of coordination between multiple operators. Audio command can play an important part in the increasing of efficiency and accuracy of operators. Audio augmentation to automatic checkout is not new. Magnetic tape systems under checkout system control provide such audio augmentation today. Multitrack tape systems where the control is by the tape itself are also used.

It is suggested that a very versatile checkout system can be designed using the combination of a small general purpose computer, perhaps a supplemental digital tape storage and a random access audio playback device such as ORATE. Very complete trouble analysis computer routines could be written on each segment of checkout of a system. These routines could be stored in inexpensive tape storage and readout of trouble analysis conclusions given to the operator aurally by ORATE. All operator instructions as to system setup for particular tests and the required results would also be given aurally by ORATE.

Such a system has the advantage of having a permanent vocabulary (made by professional announcer) and could be used in a variety of checkout tasks simply by changing the control program in the computer. When aural instructions are placed on tape a special recording must be made for each sequence of a total test sequence. It would appear also that repeating a sequence of a test could be considerably faster in a computer-random access voice checkout system.

CONCLUSION

ORATE, a random access, digital-to-voice converter, is a new and powerful tool to add to our list of input-output devices. Many new ideas in equipment development using ORATE should suggest themselves in addition to those already mentioned.

Feasibility of conversion by the technique used has been demonstrated in the developmental model built and presently under test. The developmental model is controlled by a special purpose processor-handler to produce automatic weather broadcasts. The processor-handler stores incoming teletype signals for subsequent decoding and generation of commands to ORATE to produce real time speech.

The techniques used in ORATE are all state-of-the-art. The novel means used for accessing multi-length vocabulary items is simple and fool proof. Because of this simplicity, large scale random access speech readout is now available at low cost.

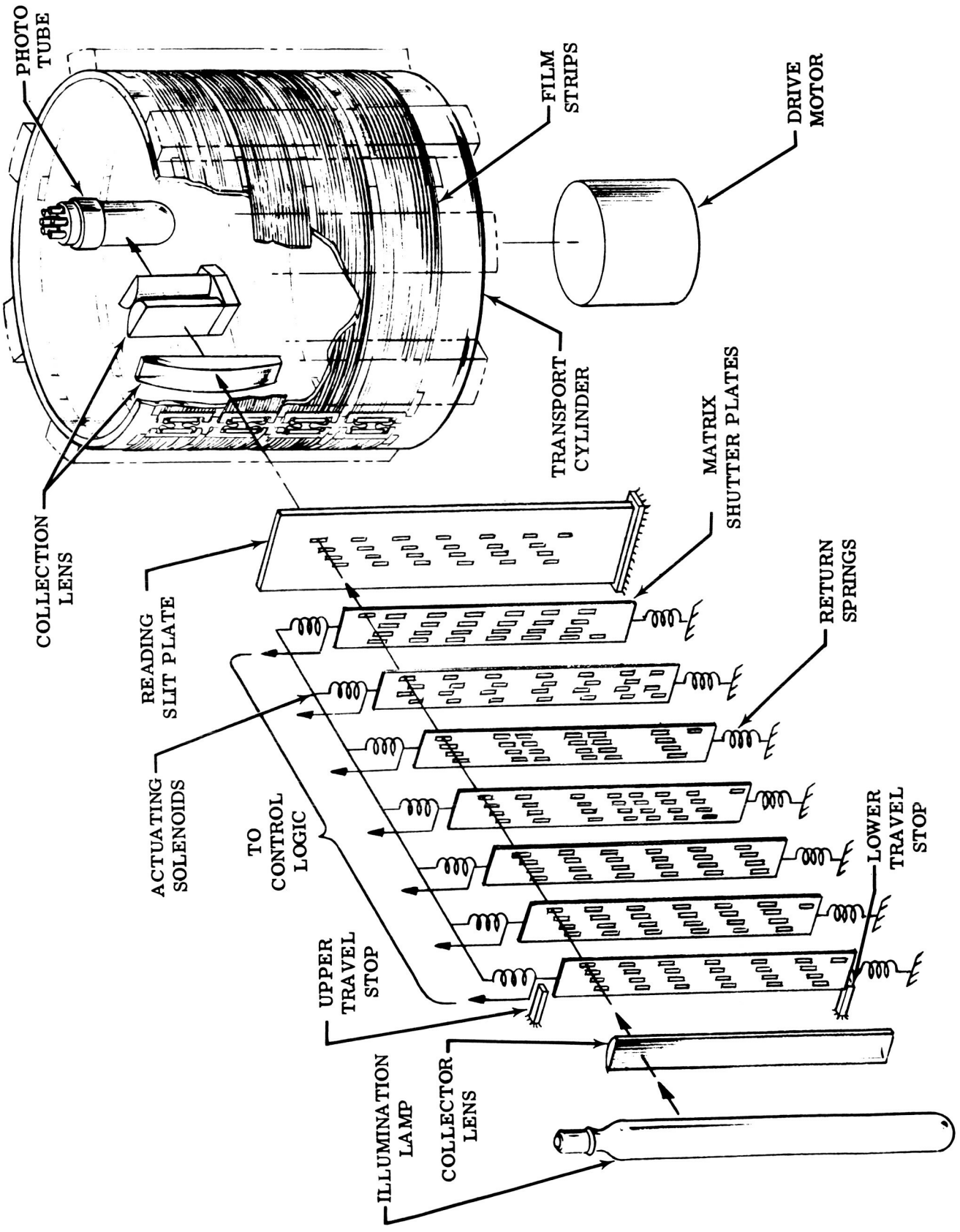

Figure 1. Orate Operating Principles

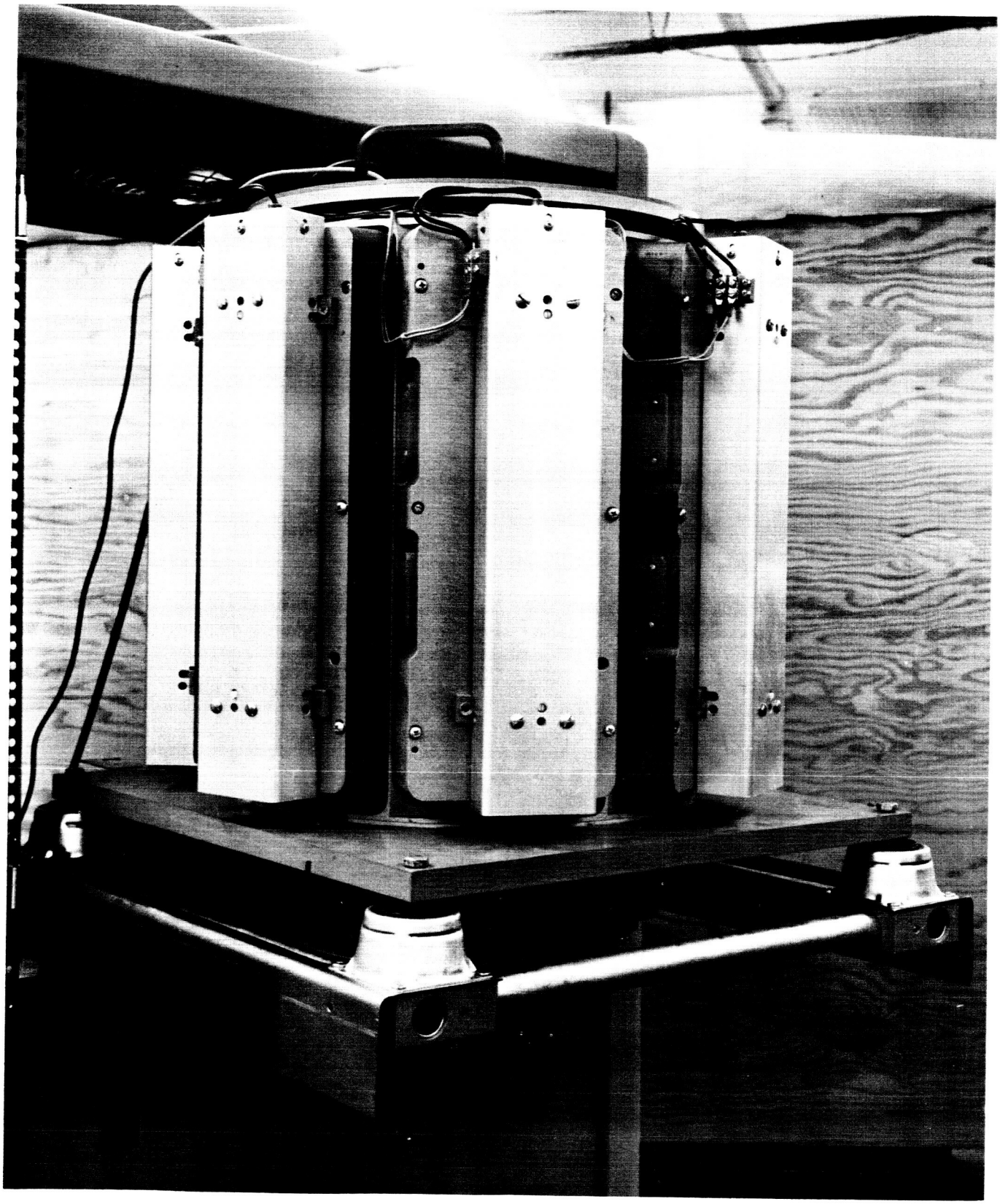

Figure 2. Operational Orate

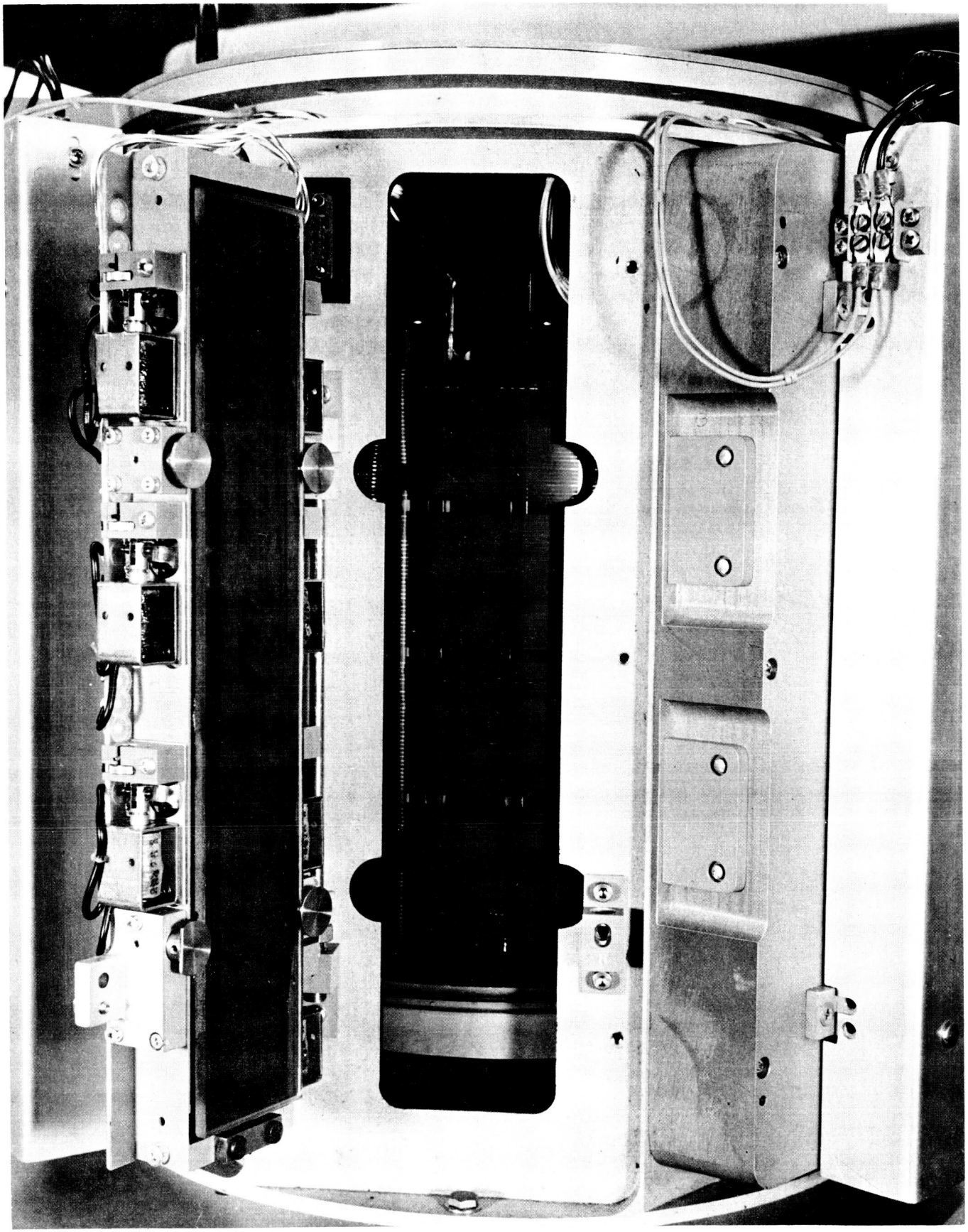

Figure 3. Orate, Showing Reading Head

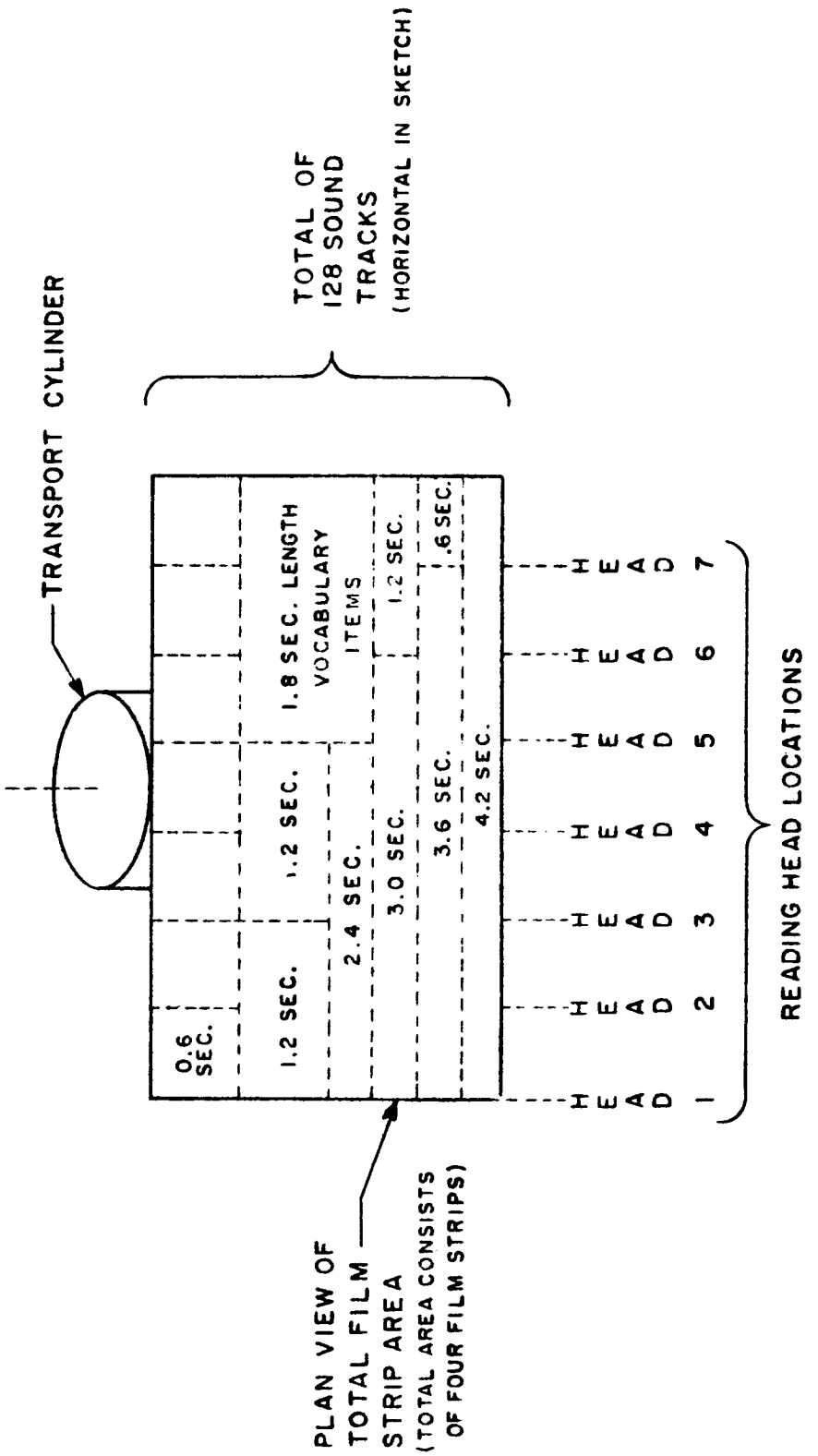

Figure 4. Typical Vocabulary Placement

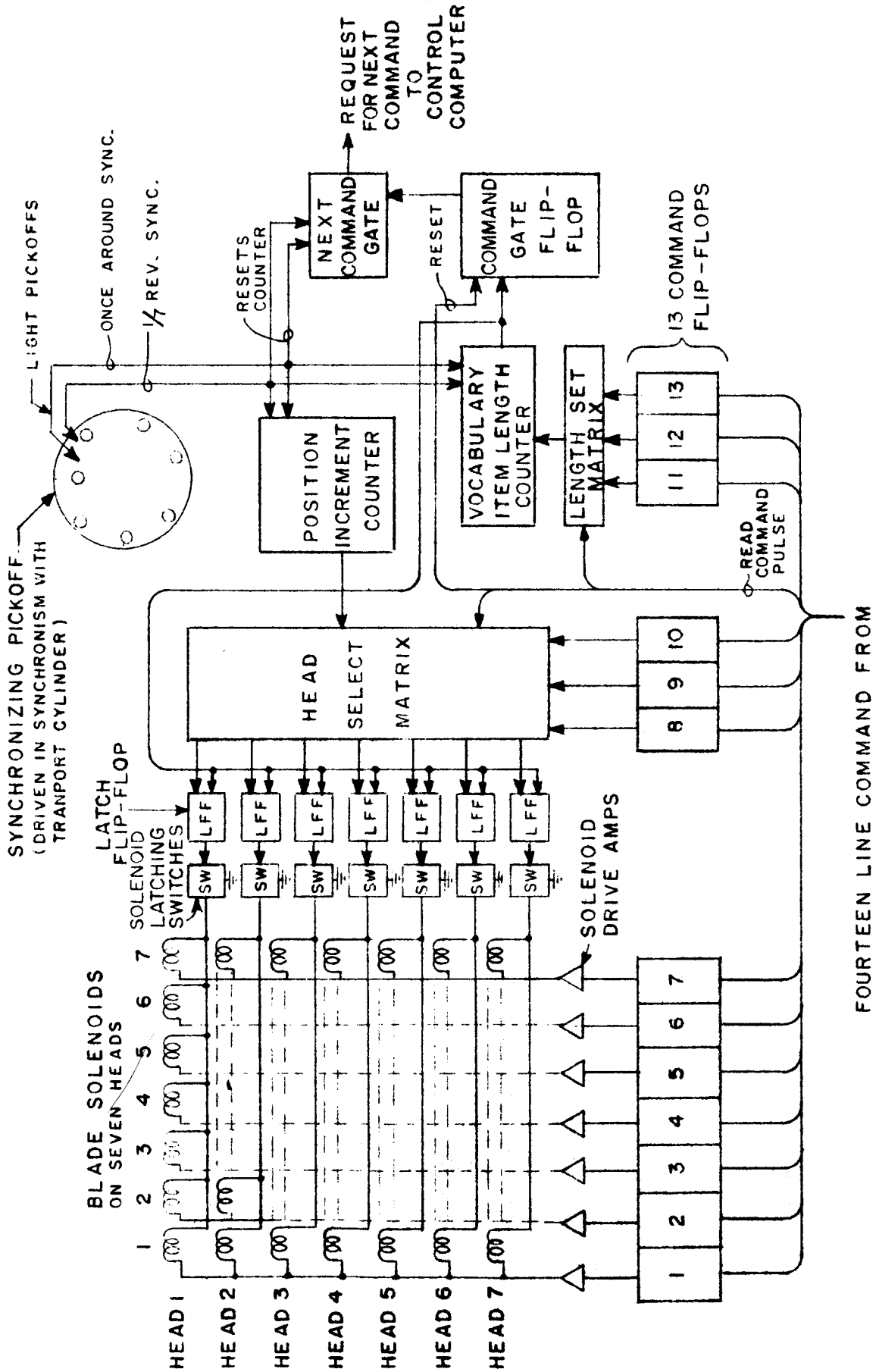

Figure 5. Orate Control Logic

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Mr. Clune received his BS in electrical engineering (Indiana Institute of Technology). He has done graduate work toward an MS in electrical engineering (University of Buffalo). He was with the Magnavox Company of Ft. Wayne before joining the Bell Aerosystems Company in 1949. He has been responsible for the design of a wide variety of aircraft and missile electronics systems developments, was program manager for the Automatic Weather Broadcast Equipment development effort, and was responsible for the conception of approach and direction of the project. Present position: Group Supervisor of digital system development in the Avionics Division of the Bell Aerosystems Company, Buffalo, New York.

JOHN J. COLEMAN, Space Technology Laboratories.

Mr. Coleman received his BS in physics (Rensselaer Polytechnic Institute) and an MS in applied mathematics (Brown University). He has spent over 15 years of professional and managerial experience on national security problems in the fields of long-range strategic strike and counterstrike forces; global systems for detecting nuclear explosions in various environments; studies on systems reliability, maintainability, spares logistics, readiness and advanced checkout techniques, and on operational analyses on the system design and cost effectiveness of national space programs, both military and civilian. Mr. Coleman is also a lecturer in Systems Engineering/ Operations Research at the University of Southern California, and has published and delivered 36 technical papers. Present position: Staff Engineer, Aerospace Systems.

DOUGLAS S. L. DURIE, Bell Aerosystems Company.

Mr. Durie received a BS degree in Engineering Physics (University of Saskatchewan). He has been employed by the National Research Council, Optics Section, in Ottawa, Canada; the Photographic Survey and DeHavilland Aircraft Corporations, in Toronto (development of airborne analogue computers for navigation and fire-control applications); Bausch and Lomb at Rochester, New York, as Section Head (mechanical design) and assisted in the design of large solar simulation systems. He has published in the areas of high-speed cinematography, refractometry, and data-reduction devices, and was responsible for the optical and mechanical aspects of ORATE design. Present position: Senior Engineer, Digital Systems Section, Bell Aerosystems Company, Buffalo.

W. SCOTT FELLOWS, NASA-Marshall Space Flight Center.

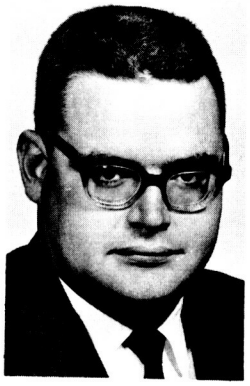
Mr. Fellows is an Air Force Colonel who received a BS degree in mechanical engineering (Ohio State University), an MS degree in aeronautical engineering (Purdue University), and a diploma from the Oak Ridge School of Reactor Technology where he studied nuclear engineering. He is a graduate of the Air Force Experimental Test Pilot School and has military decorations which include the Distinguished Flying Cross and the Air Metal. Colonel Fellows came to Huntsville in June, 1961, from Cincinnati, Ohio, where he was associated with the Lockland Aircraft Reactor Operations Office for the Atomic Energy Commission and was Assistant Manager for Technical Programs there. Colonel Fellows is a member of Sigma Alpha Epsilon and Gamma Alpha Rho fraternities, and an Associate Fellow of the AIAA. Present position: Head, Nuclear Vehicle Projects Office.

HANS J. FICHTNER, NASA-Marshall Space Flight Center.

Mr. Fichtner received his BSEE degree (Institute of Technology, Ilmenau, Germany) and was with the Heeresversuchsstelle Peeuemude. He has over 20 years' experience in the design and development of electrical systems for missiles and space vehicles, having participated in such major programs as Redstone, Jupiter, Jupiter C, Juno II, Redstone-Mercury, Saturn, and the Explorer Satellite series. Mr. Fichtner has been a U. S. citizen since 1954. Present position: Chief, Electrical Systems Integration Division.

RICHARD E. FORBES, IBM Corporation.

Mr. Forbes graduated from Northeastern University. He was a Staff Member of the Computation Laboratory of Harvard University and a member of the Computer Department of Sylvania Electric Products, Inc., before he joined IBM at the Endicott Development Laboratory where he initiated and directed IBM's major effort in applied research and development of advanced techniques and computational algorithms for the automatic generation and application of diagnostic procedures. He transferred to the Space Guidance Center in 1962, where he currently has primary technical responsibility for advanced computer applications in the design, analysis, simulation, fabrication, and checkout of aerospace switching systems. Present position: Advisory Engineer, Space Guidance Center, Federal Systems Division.



RICHARD W. FOSTER, NASA-Marshall Space Flight Center.

Mr. Foster attended Purdue University, majoring in mechanical engineering, and received the American Rocket Society National Student's Award in 1952 and 1955. He was connected with the Naval Research Laboratory at Cape Canaveral and worked on the Vanguard Satellite. He has published a number of papers on rockets. Present position: Chief, Advanced Checkout Design Unit.

KENNETH B. HOBBS, Battelle Memorial Institute.

Mr. Hobbs is with the Publications and Public Services Office and served on the Arrangements Committee for the Seminar.

WILLIAM R. IRION, Battelle Memorial Institute.

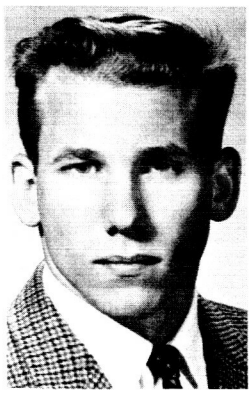
Mr. Irion received a BS degree (Capital University) and an MA degree (Ohio State University) with majors in mathematics. Active in the field of digital-computer programming since 1953, he specializes in the design and development of large-scale operating systems and problem-oriented languages and their compilers; he has worked on all the IBM machines from the CPC on, maintained the FORTRAN II and APT II operating systems, developed the SCATRAN for OSU 709/7090 Operating System, developed a source-language debugging system as part of the COBOL compiler-operating system for the Control Data G-20 and is presently working on PLACE. He is a member of the ACM and Central Ohio ACM. Present position: Senior Mathematician, Computation Center Group.

BRADFORD T. JOYCE, Radio Corporation of America (Burlington).

Mr. Joyce received his BS degree (University of Maine) and his MS degree (M.I.T.). He has been active in designing and developing aircraft fire- and explosion-detection equipment and specialized test equipment for infrared-sensitive devices; a variety of transistor circuits for airborne fire-control systems and checkout equipment. He had the responsibility for the electrical and mechanical design of the automatic programmed checkout equipment (APCHE) for the ATLAS missile; supervised the development of the RCA AM1100 digital differential analyzer and two general-purpose digital computers, the AM3100 and the AM3220; and was associated with the design and development of Multisystem Test Equipment (MTE) for the Army. Present position: Project Engineer for MTE test programming.

ROBERT A. KIRKMAN, Space Technology Laboratories, Inc.

Mr. Kirkman studied electrical engineering (C.C.N.Y.), graduated with a certificate in communications engineering (RCA Institute Resident School), and has done extensive graduate work in microwaves, mathematics, control systems, and space technology (Rutgers University), (U.C.L.A.). He has 23 years of experience in commercial and military electronics in the fields of ground radars and automatic weather stations; participated in early White Sands firings; airborne beacons, data-handling systems, and computers. His systems experience includes project engineering, program management and design integration for the Atlas missile; the F-106 and F-108 interceptors; high-speed, internally programmed, automatic checkout equipment design for Wizard, Nike-Zeus, Skybolt, Pershing and Apollo; and he is the author of several papers on systems testability, checkout, and reliability. Mr. Kirkman is a Senior Member of the IEEE and of several of its Professional Groups. He has held several IRE offices and is a Past Chairman of the San Diego Section. Present position: Minuteman Project Engineer on Ground Equipment.



OWEN B. LAUG, National Bureau of Standards.

Mr. Laug received a BSEE degree (University of Maryland). He is presently on the staff of the NBS graduate school. Mr. Laug has worked at the National Bureau of Standards 4 years, and is a member of the Institute of Electrical and Electronics Engineers. Present position: Project Engineer.

ARTHUR E. MACE, Battelle Memorial Institute.

Dr. Mace obtained his BA degree (Amhurst College) and his PhD degree (University of Chicago). Since joining Battelle in 1956, Dr. Mace has been primarily engaged in engineering applications of probability and statistics. His work has included experience in stochastic processes, experimental design, error analysis, statistical inference, and the use of automatic computers for statistical analysis. At present he is engaged in the development of probabilistic models to represent deterioration and failure processes in electronic components and systems in the formulation of statistical procedures for their estimation from experimental data so as to provide the basis for maintenance or replacement policy. Dr. Mace has written technical papers that have been published in the Harvard Review of *Economics and Statistics* and *Industrial Quality Control* (in press). He is a member of the American Statistical Association, American Society for Quality Control, Econometric Society, and the American Economic Association. Present position: Assistant Chief in the Mathematics and Theoretical Physics Division.

VICTOR MAYPER, JR., Hughes Aircraft Company.

Dr. Mayper received his BS and PhD degrees (M.I.T.). He has worked on microwave magnetrons and low-temperature physics at the M.I.T. Research Laboratory of Electronics; on field engineering of a telemetry system for nuclear-weapons-effects measurement; and on new methods of geophysical prospecting for minerals. Since 1955, he has been associated with Hughes Aircraft Company, working on logical design, computer test equipment, system self-tests for various systems, and the design and application of automatic test equipment and systems. His publications include papers on noise in magnetrons, second sound, and induced-polarization prospecting, and he has lectured at U.C.L.A. Dr. Mayper is a member of Sigma Xi, American Physical Society, IRE, and ACM. Present position: Assistant Manager, VATE Systems Department.

FRANK MEDVED, Aeronautical Division, Honeywell Regulator Company.

Mr. Medved received his BEE degree (University of Minnesota). Before joining Honeywell, he was a development engineer at the Electronic Division of General Mills where he had design responsibility for several hybrid, analog-digital, data-handling systems, and peripheral equipments for the AD/ECS 37 digital computer. In 1962, Mr. Medved joined the Aerospace Support Equipment Group at Honeywell where he is involved in the design of digital checkout equipment. Present position: Development Engineer, Aerospace Support Equipment Group.

GEORGE F. MEISTER, JR., Douglas Aircraft Company.

Mr. Meister received a BSEE degree (Purdue University) and has done graduate study in computer design and advanced engineering mathematics (U.C.L.A.). He participated in the design of launch and checkout equipment for the operational Thor System until June, 1960; participated in the preliminary and detailed design of launch and checkout equipment for the Saturn S-IV from June, 1960, to February, 1962; acted as Technical Assistant to Supervision for the S-IV launch and checkout system until May, 1962. In May, 1962, he was assigned the system-design responsibility for the S-IVB Automatic Checkout System and participated in the preliminary design of the checkout system and preliminary definition of the programming effort. Present position: Supervisor, S-IVB System Design.

ROGER L. MERRILL, Battelle Memorial Institute.

Mr. Merrill is the Manager of the Engineering Physics Department which organized both Seminars on Automatic Checkout Equipment and Techniques. He also served as toastmaster for the luncheon on November 14.

KAJ L. NIELSEN, Battelle Memorial Institute.

Dr. Nielsen is the Director of the Systems Analysis Group and served as Chairman of the Seminar.

JOHN C. O'BRIEN, Nortronics Division, Northrop Corporation.

Mr. O'Brien received his BS degree in physics and mathematics (University of Rochester), and has completed the MS requirements (U.C.L.A.). He was employed in the radio broadcast field (1931-1943); by the General Railway Signal Company of Rochester, New York, as Mobile Communications Project Engineer; by Convair Division of General Dynamics in Pomona, California, as missile system analyst (1952-1956); by the Associated Missile Products Company, Pomona (1956-1960). In 1960, Mr. O'Brien was employed by Nortronics Division of Northrop as a Senior Systems Specialist, and developed the SPAN methodology for system analysis and integration. He is a registered Professional Engineer in New York and California, and holds 15 patents in electronics and communications. Mr. O'Brien is a senior member of the IEEE. Present position: Senior Technical Specialist.

M. C. PETERSON, Space Technology Laboratories, Inc.

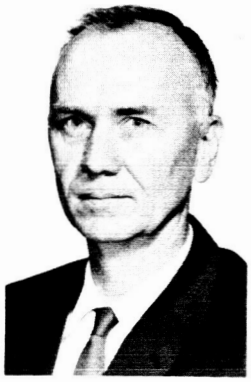
Mr. Peterson received the BEE degree in electronics in 1950 (University of Southern California). He did further graduate work in engineering and business administration from 1952 to 1961 (U.C.L.A.). From 1950 to 1959, he was employed by Bendix Aviation and in 1959 he joined Space Technology Laboratories as a member of the technical staff, working on Able space-probe system test and launch control equipment development. He is presently engaged in preliminary design, development, and evaluation of semiautomatic systems checkout equipment for space-probe and ballistics-weapon system programs. Mr. Peterson has participated in the courses given at U.C.L.A. on Ballistic Missiles and Space Vehicles, and in Automatic Checkout. Present position: Head, Systems Engineering Section, Support Systems Department.

GEORGE ROGERS, Battelle Memorial Institute.

Mr. Rogers is a Research Advisor and served on the General Committee for the Seminar.

GUSTAVE SHAPIRO, National Bureau of Standards.

Mr. Shapiro received his BSEE degree (George Washington University). He has been editor of the IRE Transactions on Component Parts since 1955; has served as a member of the National Administrative Committee of the Professional Group on Component Parts since 1952 and on the National Administrative Committee of the Professional Group on Microwave Theory and Techniques since 1957; has been on the Technical Program Committee and/or an organizer of sessions for the IRE International Convention since 1956; currently he is Chairman of the committee responsible for setting up the sessions covering component parts, production techniques, materials, and quality control for the 1964 IEEE International Convention. He is a Fellow of the Institute of Electrical and Electronics Engineers (formerly the Institute of Radio Engineers), and a Fellow of the Washington Academy of Sciences. Present position: Chief, Engineering Electronics Section.

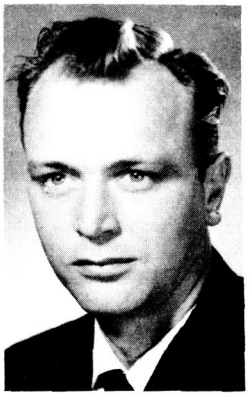


ROBERT L. SMITH, JR., NASA-Marshall Space Flight Center.

Mr. Smith received a BEE degree (University of Louisville) and a MSE degree (University of Florida). He left the professorial ranks in 1951, has been active in guidance and control work since that time, and specializes in automation of space-vehicle stage checkout. He has written papers on electrical equipment, prelaunch readiness, and is the author of "What's Right and Wrong with our Missile Test Philosophy?". He is an Associate Member of IEEE. Present position: Research Project Engineer, Technical Staff, Quality and Reliability Assurance Laboratory.

CARL W. STEEG, JR., I.T.T. Industrial Laboratories (Ft. Wayne).

Dr. Steeg received an AB degree (DePauw University, Michigan State), BSEE degree (Oregon State) and PhD degree (M.I.T.). He has been active in the fields of systems analysis, evaluation, analog and digital computation and flight simulation of guided weapons; synthesis of nuclear-reactor controls, autopilots, and stability and control augmentation devices for guided and ballistic weapons; statistical optimization theory in nonlinear, adaptive, and sampled-data control systems; automatic checkout and malfunction detection techniques; human factors; sensors, instruments, and data processors. He has held many supervisory positions. He is a Fellow of the American Association for the Advancement of Science, and is a member of the American Mathematics Society, American Ordnance Association, Sigma Xi, and the Society of Industrial and Applied Mathematics. Present position: Director, New Product Planning and Development.

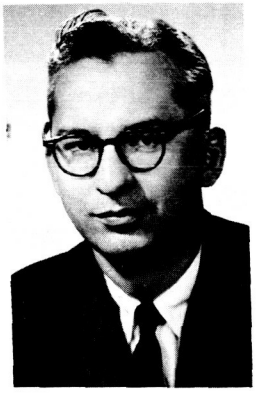


EUGENE M. STOCKTON, Radio Corporation of America (Burlington).

Mr. Stockton received his BSEE degree (Michigan State University) and his MSEE (Drexel Institute of Technology). At the RCA Defense Electronic Products, Airborne Systems Division, he was assigned to the design and development of the Air Force ASG 14 fire-control system where he worked on power supplies, receivers, transmitters, and synchronizers for radar devices; he has gained experience in every facet of Automatic Test Equipment with particular emphasis in system design, computer-controller design, and system integration and test. As design leader, he was responsible for the design of the computer used in the Multisystem Test Equipment developed for the Army Missile Command. Present position: Design Leader.

B. D. THOMAS, Battelle Memorial Institute.

President.



MICHAEL TIKSON, Battelle Memorial Institute.

Mr. Tikson is the Director of the Computation Center and served on the Program Committee for the Seminar. He was also Chairman, Tutorial Session II.

STUART H. VOGT, NASA, Headquarters, Washington, D. C.

Mr. Vogt received his BSEE (Lehigh University). He has been associated with the Bureau of Naval Weapons, Pacific Missile Range in range instrumentation development and the Launch Operations Directorate, Office of Launch Vehicle Programs, NASA. He is a member of IEEE. Present position: Head, Flight Readiness and Launch Section, Office of Advanced Research and Technology, NASA.

BURTON H. WENT, Battelle Memorial Institute.

Mr. Went received his BS degree (University of Portland). Before joining Battelle, Mr. Went worked with digital computers, designing and implementing an operating system for the FORTRAN compiler, and did some work on the SURGE data-processing compiler for the 704. Since joining Battelle, he has performed research to develop a problem-oriented language for automatic checkout equipment; has helped develop and implement a NELIAC compiler for the G-20; and was the project leader for Battelle's effort in the development of a COBOL system for the G-20. Mr. Went is a member of the Association for Computing Machinery and the Central Ohio Association for Computing Machinery. Present position: Project Leader, Automatic Checkout Programming Language.

F. S. WOJTALIK, NASA-Marshall Space Flight Center.

Mr. Wojtalik received his BEE degree (Michigan State University). His work requires that he accomplish advanced technical planning in the area of operational process control for the Saturn Operational Computer System and orbital checkout functions of the vehicle-borne computer complex. His experience in ground-support equipment has been gained through design and development projects for the Redstone, Jupiter, and Pershing missiles as well as the Saturn vehicle program. Present position: Technical Assistant to the Division Chief, Guidance and Control Division.

ROBERT YEREANCE, Battelle Memorial Institute.

Mr. Yereance is the Program Director for Reliability and served on the General Committee for the Seminar. He was also Chairman, Tutorial Session I.

PHIL YOUNGBLOOD, NASA-Marshall Space Flight Center.

Mr. Youngblood is the Deputy Chief of the Electrical Systems Integration Division, and was the coordinator for the NASA presentation and served on the Programs Committee for the Seminar.